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The Journal of
THE ROYAL AERONAUTICAL SOCIETY

CONTENTS JULY 1951

PROGRESS TOWARDS ELECTRICAL SERVICEABILITY
R. H. WOODALL, M.I.E.E., A.F.R.Ae.S., and V. A. HIGGS, B.Sc., A.M.I.E.E., A.F.R.Ae.S.

PROGRESS TOWARDS HYDRAULIC SERVICEABILITY
R. H. BOUND, F.R.Ae.S., and H. G. CONWAY, M.A., M.I.Mech.E., F.R.Ae.S.

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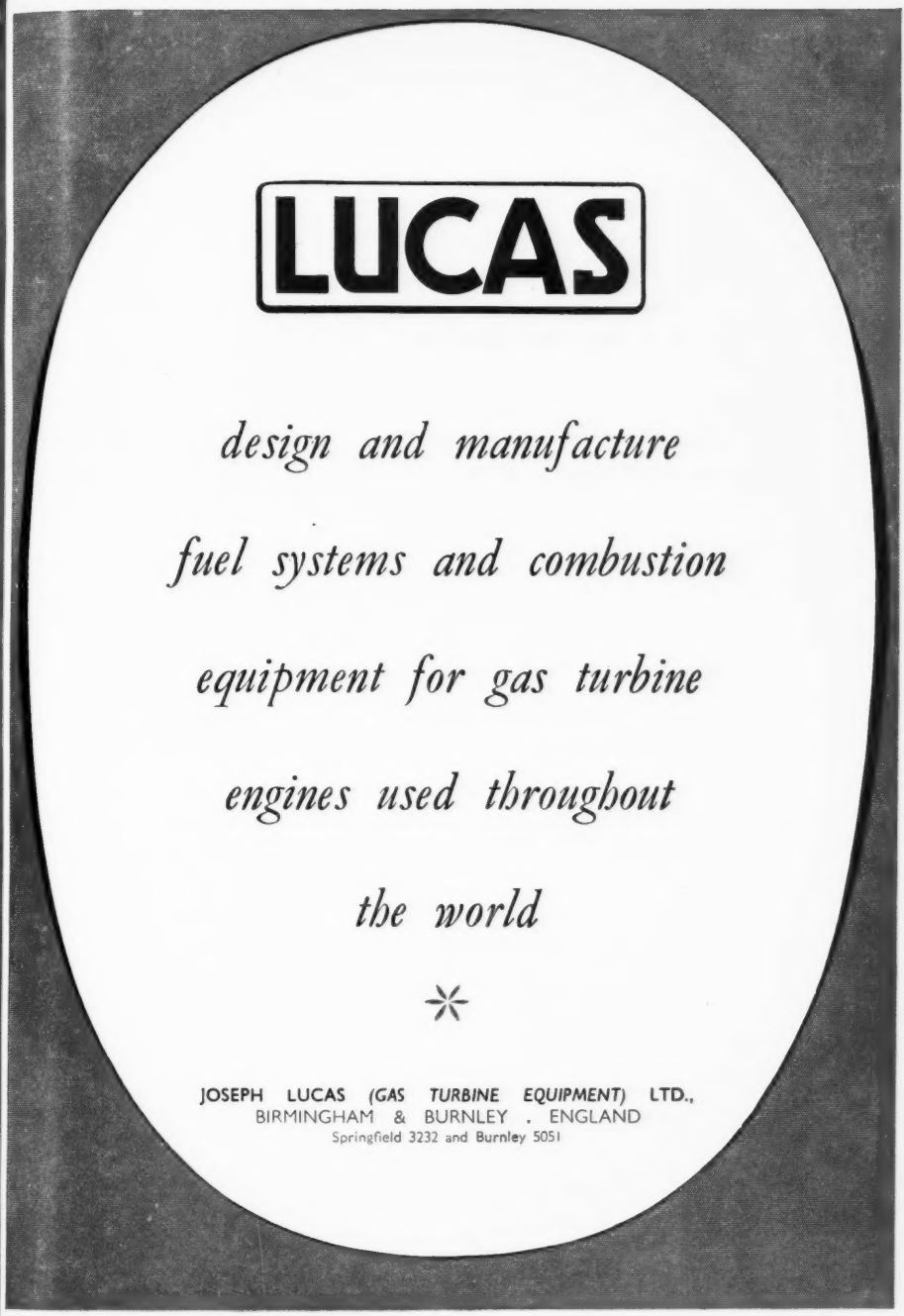
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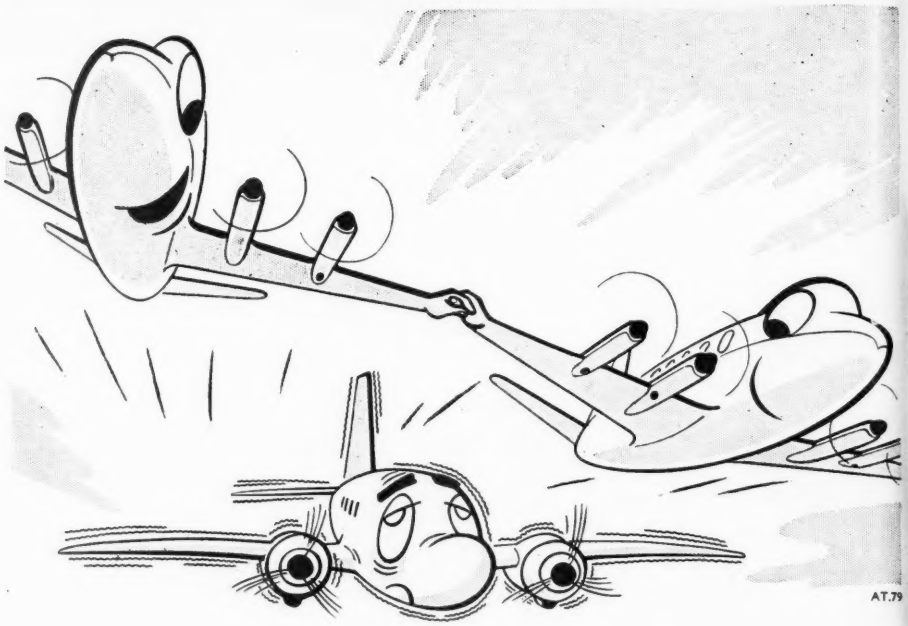

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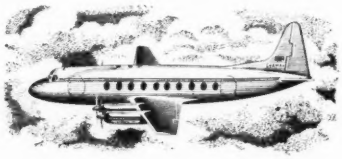

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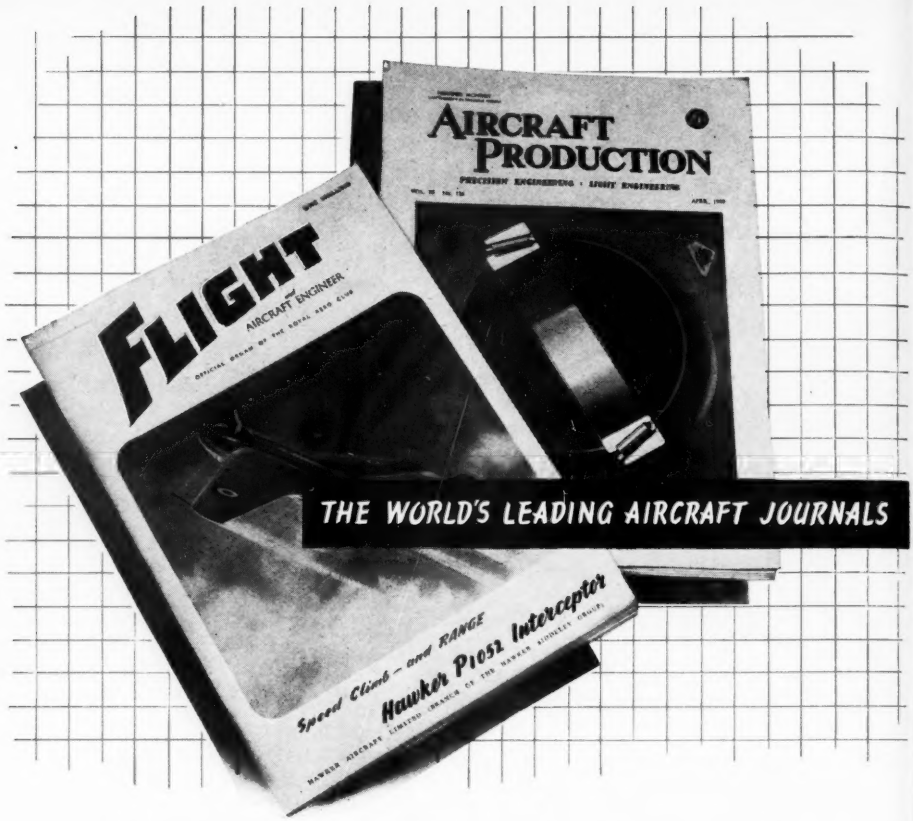

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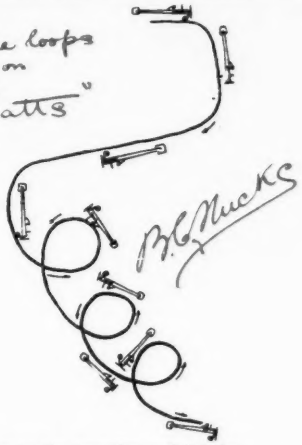
WHEN fame and fortune rewarded the flyers of Kitty Hawk, Wilbur and Orville kept their heads. The Wright Brothers were singularly and dually unimpressed, John Dos Passos has told us, "by the upholstery and the braid and the gold medals and the parades of plush horses." They remained humble mechanics; they serviced their machines with their own hands—" even to filling the gasolene tank."

Wise men.

In those days even the ESSO service (yes, the Wrights used the products of ESSO's forebears) was somewhat sketchy and . . . well, a trifle gimcrack. But that was 1903.

Remember pre-1914 Hendon? B. C. Hucks? Below is his own diagram of loops done on Pratts—ESSO's godparents in Great Britain—reproduced from an advertisement in "The Aeroplane" of December 18th, 1913. Bunting a Blériot! Ugh!!



Now turn to the twenties and thirties.

Giant strides? Yes and no. Croydon was then Britain's one and only international airport, and the refuelling service at Croydon consisted of two men, a dog and a battery of the familiar road-side petrol pumps. At smaller aerodromes the two-gallon tin and funnel was still the standard refuelling equipment. The day of *intensive* development had not yet arrived.

But *extensively* there was much ado. New airfields were appearing every week. The Hinklers, Scotts and Blacks, Earharts, Lindberghs, Kingsford Smiths were touching down here, there and anywhere; and wherever they landed they expected to find fuel ready and waiting. Yes, the refuellers beat the flyers to Conakry, Ouagadougou, Yoff, Zinder, Usumbura, Windhoek, Ratmalana, Kai Tak, Dum Dum, Kuching, Lakunai, Darwin, Garbutt . . . They had to; *had* to.

And it wasn't always easy. Isn't even now. In the Sahara fuel reaches the landing-grounds by camel; in the South Seas it goes in by tank-landing craft; elsewhere it's supplied by pack-horse, by

raft, tanker, barge, tank-car, pipe-line. And not just any old fuel, for even in the remotest airfields air superintendents have a habit of specifying "80" or "100/130" or "108/135" or "115/145", and it's ESSO's job to see that they get it.

It's a biggish job.

Now jump to 1951. The scene: London Airport. Our two men and a dog have become a team of thirty expert refuellers (and a dog) armed with four 3,300-gallon tankers and a new 4,000-gallon unit capable of delivering the goods at more than 300 gallons a minute any time day or night. Petrol plus oil, water-methanol, de-icing fluid, plus . . .

Refuelling in complete safety at top speed—everywhere. That's 1951. Prestwick: twenty minutes scheduled for a re-fill of 2-3,000 gallons. Shannon: 10,283,561 gallons of ESSO piped into 4,883 airliners in one year (eighty per cent. of all aircraft using the airport!). Gander . . . Goose Bay . . . Elmdon, Renfrew, Jersey, Speke, Bovingdon, Croydon, Northolt, Ringway . . . everywhere, it pays to say ESSO.

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It is no secret that ESSO's world-wide service is the product of long experience and indefatigable research—experience won the hard way and paid for by the confidence and co-operation of the pioneers, and research by the boys in the not-so-small back rooms of ESSO's £5,000,000 a year laboratories.

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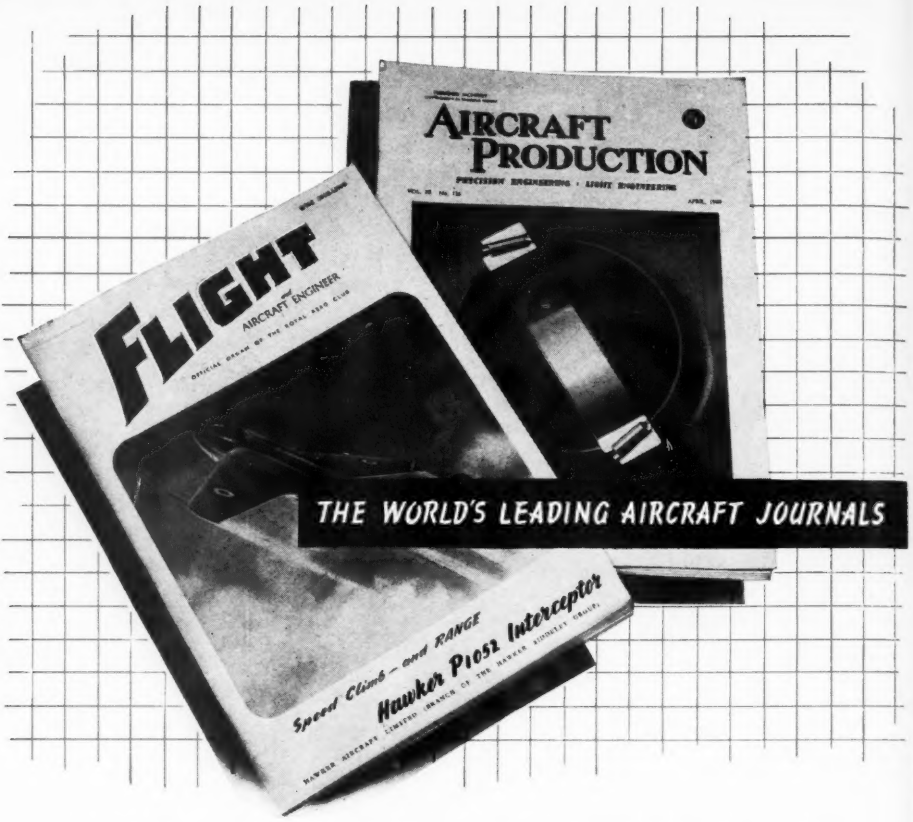

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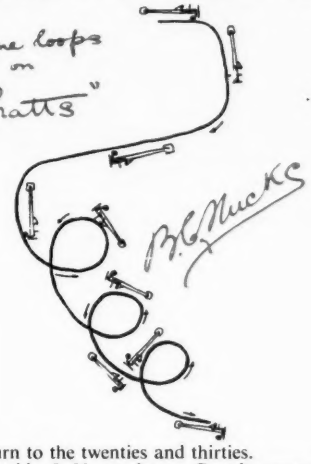

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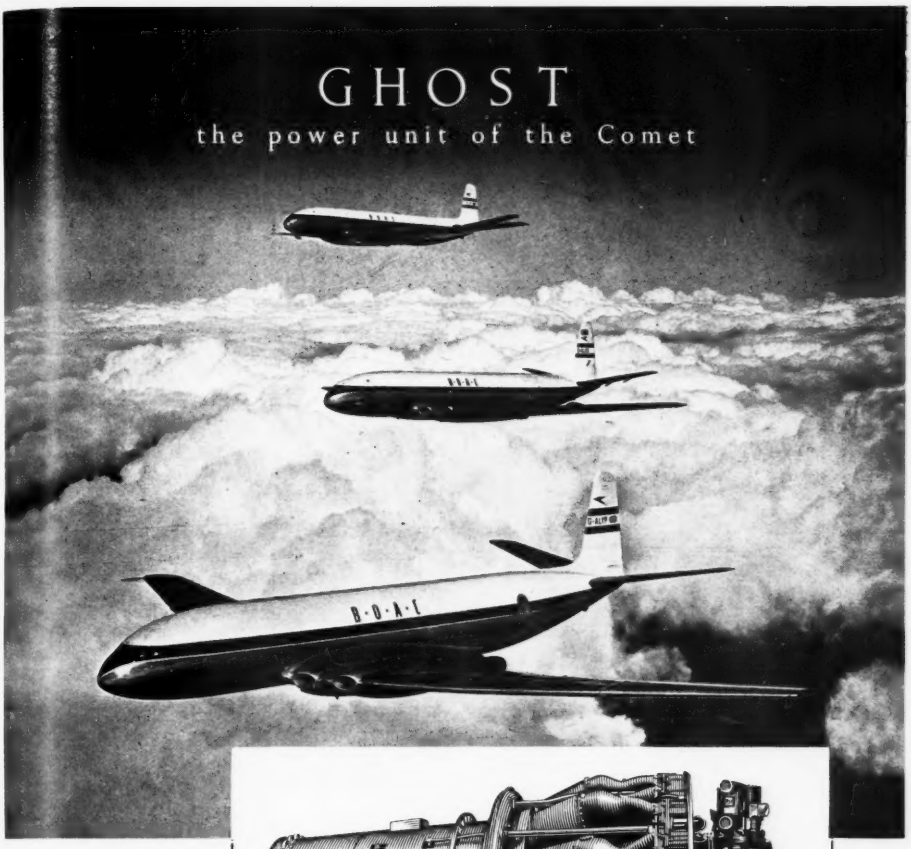

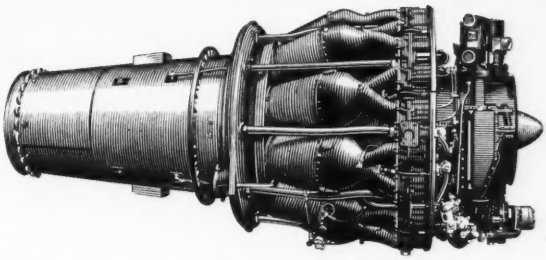

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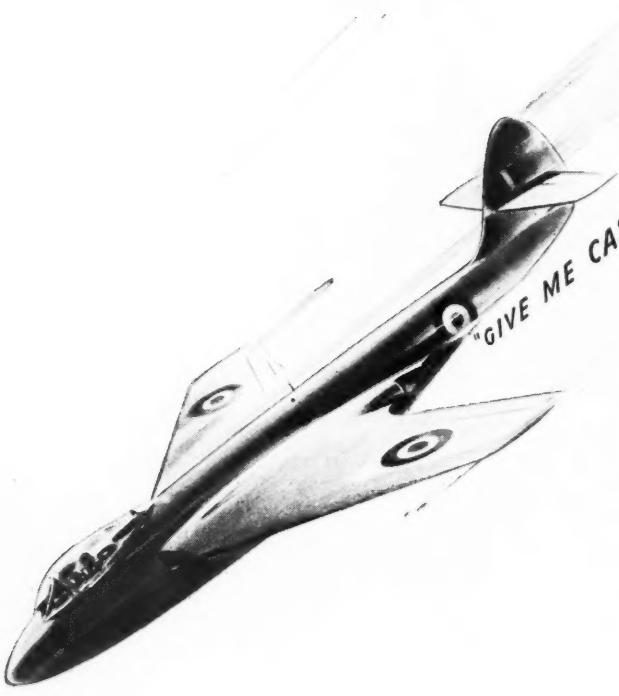

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PROGRESS TOWARDS ELECTRICAL SERVICEABILITY

by

R. H. WOODALL, M.I.E.E., A.F.R.Ae.S.

and

V. A. HIGGS, B.Sc., A.M.I.E.E., A.F.R.Ae.S.

THE 820th Lecture to be read before the Royal Aeronautical Society, "Progress Towards Electrical Serviceability," was given by R. H. Woodall, M.I.E.E., A.F.R.Ae.S., and V. A. Higgs, B.Sc., A.M.I.E.E., A.F.R.Ae.S., on 1st March 1951 at the Institution of Civil Engineers, Great George Street, S.W.1. Major G. P. Bulman, C.B.E., F.R.Ae.S., President of the Society, presided at the meeting and introduced the lecturers. Mr. Woodall is a Director and Chief Engineer of Rotax Ltd., and Mr. Higgs is Head of Technical Sales and Aeroplane and Automobile Sales of the British Thomson-Houston Co. Ltd.

1. INTRODUCTION

It is evident from remarks made in previous papers or in discussion on those papers, that the Aircraft Industry is not entirely satisfied with the electrical accessories available for use in aircraft.

There may be some grounds for this dissatisfaction, but it is hoped to make it clear that the electrical equipment suppliers are very much alive to their responsibilities and that development on an ever-increasing scale is taking place in order to give the aircraft constructors the most reliable equipment possible.

Electricity has now become the main servant of mankind. In normal times, the electrical generation plant of Great Britain provides a thoroughly reliable service of electrical energy to consumers and the majority of the utilisation equipment taking current from this supply is equally reliable.

Reliability must bring in a time factor, and it would be foolish to expect aircraft equipment to give equal reliability to that of industrial equipment, bearing in mind the great difference in their power-weight ratios and the vastly different conditions under which they have to operate.

A compromise is necessary, therefore, and the authors have assumed that reliability, minimum weight, and ease of maintenance can be grouped under the term "serviceability" and that with a design of the lightest weight, the reliability shall be such that "x" flying hours can be operated before maintenance of any kind is necessary. Furthermore, the maintenance necessary after "x" hours shall be a minimum—and this servicing shall be done with the smallest number of man hours.

The paper attempts to suggest a value for "x" and it is hoped that the discussion will bring out the views of designers and users on this factor.

The paper outlines the steps which the electrical engineer has taken, or is taking, towards improving the serviceability of his equipment.

2. THE AIRCRAFT PROBLEM

The electrical power system of an aeroplane can be split up in the same manner as a national electricity undertaking into three parts—generator, transmission and distribution and utilisation equipment.

In normal times power stations, transmission lines and utilisation equipment all have a very high degree of reliability but, except for its effect on cost, the weight of equipment is unimportant.

Figure 1 shows the variation in specific weight or lb./kw. output of industrial

alternators as compared with aircraft alternators. For sizes below 10,000 kw. it is extremely difficult to decide what is a typical industrial alternator and the curve shown can only be considered as approximate. It is interesting to note that the large turbo-alternators of 50,000 kw. output or more do approach the same power/weight ratio of the very small output aircraft alternators.

Similarly with motors—Fig. 2 shows the stator and rotor units, or active parts, of a number of different one h.p. motors. It will be seen that the size decreases as the speed increases. With an A.C. motor the speed increase beyond 3,000 r.p.m. is achieved by increasing the supply frequency and the 60,000 r.p.m. machine is operating at a frequency well above the optimum. The woodworking machine is a 2-pole 300 cycle unit and the aircraft machine is a 4-pole 400 cycle unit and both are operating at near the optimum frequency. Thus a comparison between the woodworking machine and the two aircraft motors shows how much has been achieved towards high power/weight ratio. If the motor weights are considered on a torque basis or lb./hr./r.p.m., then it will be seen that weight does not decrease in proportion to the speed increase and there is the paradox that, provided the industrial machine is run slow enough (*i.e.* make it bigger), then the aircraft motor weight expressed as lb./h.p./r.p.m. can be improved.

In aircraft applications it is usual to increase the torque output by the use of gearboxes and for one h.p. 1,500 r.p.m. the aircraft motor would need the addition of a 6.2/3 : 1 ratio gearbox, probably weighing one or two pounds, so that the aircraft unit is considerably lighter than the industrial machine.

Now whereas industrial equipment normally operates under reasonably easy conditions as regards temperature and humidity, and without the application of external vibrations and accelerations, the aircraft picture is a vastly different story.

2.1. Requirements

Aircraft electrical equipment has to comply with countless specifications, many of which are necessary to ensure the serviceability of equipment under working conditions.

Temperature

Apparatus must now operate in any ambient temperature from −70°C. to +50°C. and in some cases +90°C., and it is likely that electrical equipment associated with the power plant of some of the latest turbines will have to function in even higher ambients.

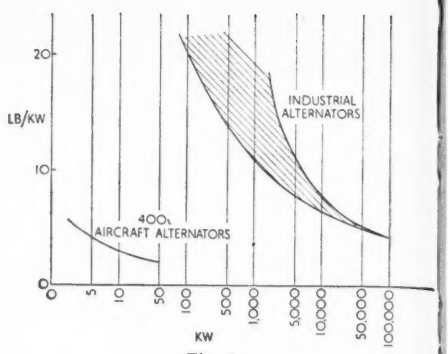

Fig. 1.
Power/weight ratio of alternators.

Utilisation equipment, such as actuators for undercarriages, flaps, nose wheel steering, and so on, must operate satisfactorily after rapid descent from altitude, *i.e.* after having been soaked at a temperature as low as −70°C.

This means that insulating materials, solders and other materials, must withstand these wide temperature differences without deterioration, and lubricants must not be solid at the minimum temperature nor fail at the highest temperature.

Density

Outside air densities from sea level to 60,000 feet have to be faced. Reduced density has the effect of increasing the temperature rise of machines cooled by fan or ram air. This is shown approximately in Fig. 3, which plots maximum permissible temperature rise at sea level to ensure that limiting temperatures are not exceeded at any altitude.

It can be shown that the temperature rise of a ram air-cooled machine at 50,000 feet is 2.5 times that of the temperature rise of the machine at sea level. Therefore with the maximum air temperature at 50,000 feet taken as −30°C., the sea level temperature rise must not exceed 70°C. if the maximum temperature of the machine is not to exceed 150°C. at altitude. A more thorough investigation into the problems of cooling at altitude is required.

Reduced density also has the effect of reducing the spark-over distance for any voltage and this is an important factor in the design of ignition apparatus and switchgear for high altitude work.

Sudden increases in air density often cause moisture to be drawn into electrical components during rapid descent of aircraft from high altitudes.

Humidity and fungus growth

Electrical equipment must work under conditions of high humidity and often in a water spray. This means complete hermetic sealing of the apparatus or the adoption of non-hygroscopic insulating materials and the full protection of all metallic parts against moisture and very often salt-laden atmosphere.

All apparatus must resist the formation of fungus growth, which means that certain materials cannot be used and others must be specially treated.

Vibration

There must be no deterioration of apparatus subject to the vibrations occurring in the engine or aircraft structure to which it is mounted.

For reciprocating-engined aircraft, for which a vibration specification exists, the maximum amplitude in the engine nacelle may be 0.030 in. at 10 cycles and 0.005 in. at 500 cycles.

For turbine and propeller-turbine aircraft, no adequate specifications are in existence yet.

Flame-proofness

Most apparatus must be flame-proof and must operate satisfactorily in the presence of petrol, oil, and their vapours, and also hydraulic fluids. This often means the introduction of flame traps, which, with fan-cooled machines can become an obstruction to the air flow necessary for the adequate cooling of the machine, particularly if the atmosphere in which the machine operates has oil vapour present.

Fire-proofness

Equipment such as feathering pump motors and certain motorised cocks, the use

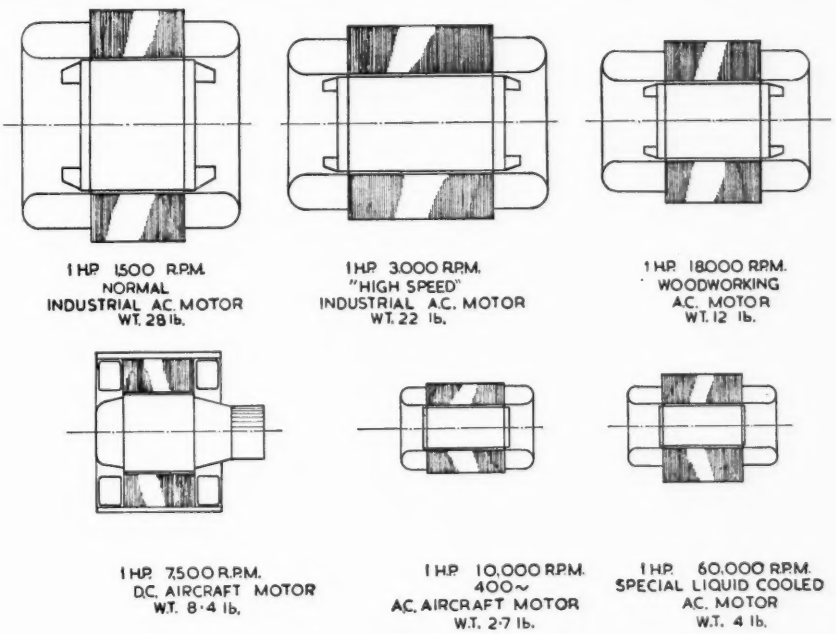

Fig. 2.
Size and weight of electric motors.

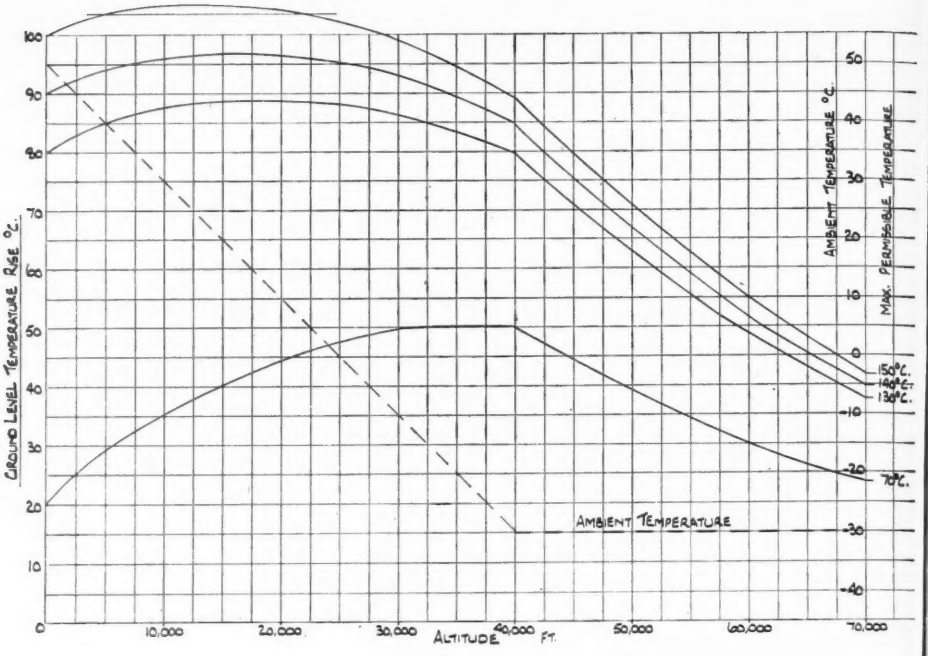

Fig. 3.
Temperature rise of blast cooled machines at altitude.

of which is necessary in the event of a fire in the engine nacelle, must pass a fire-proof test in which the flame of one or more blow-pipes is directed on to any part of the carcase of the machine.

Voltage range

Utilisation equipment must often operate over a wide voltage range. The reason for this is not always obvious to the designer, and some suggestions to avoid this will be mentioned later in the paper.

Speed range

Unlike power station generating plant, aircraft generators must give maximum output from minimum or idling speed of the engines and must run without damage at maximum take-off speed. The speed range may be 3:1 to 4:1, although 5:1 has also been suggested for certain military requirements of the future. The effect of this is discussed more fully later.

The very marked difference in the conditions of operation of industrial and aircraft equipment and also in their respective power-weight ratios, shows the difficulty of approaching the reliability of the heavier equipment in the use of lightweight equipment under the exacting conditions outlined.

2.2. The target and the difficulties in achieving it

A figure of 1,000 hours for "x" has been agreed upon as a target by many of the leading air operators, and this target is also included in some of the latest Ministry of Supply specifications for electrical accessories.

There is a feeling, however, that the weight aspect may be regarded, at any rate by the aircraft designer, as being the prime consideration for equipment for high performance military aircraft and that 250 to 500 hours for "x" might be a more realistic figure at which to aim, particularly if this would result in lighter equipment.

The standardisation of electrical equipment for both military and civil aircraft is naturally a desirable aim from the economic aspect, but it has been learned the hard way that military aircraft equipment developed under war-time conditions is not really suited

for civil applications. The opposite may be equally true.

Numerous cases can be instanced of equipment which has operated without serious troubles on military aircraft before and during the 1939-45 War; yet identical equipment has been a constant source of trouble to the airline operator. Magnetos fitted to one of the best, and certainly the most widely used, engines for fighter aircraft, when used by airline operators on civil engines of the same basic type, seldom had an operating life of more than 300 to 400 hours and the engine manufacturers were very much in the same position.

Two to three years intensive development, supplemented by thousands of hours of flying with modified equipment, has been necessary to increase the life before maintenance to 1,000 hours.

Obviously some of the snags which came to light might have been discovered by R.A.F. personnel in normal peace-time operation but, even so, it is always difficult to find military aircraft which operate long hours in anything like reasonable time and still more difficult for an electrical contractor to gain very much in the way of accurate logs of hours operated with any particular piece of equipment by the various Commands.

Other major changes necessary on these magnetos were due to certain subtle differences between the military and the civil engine, resulting in the magneto being subjected to higher temperature, increased vibration and other marked differences in the operating conditions.

The major difficulty facing the electrical industry is the question of delivery time, since "x" can only be predetermined by experience and in any case must be confirmed by flight tests. It is the time required to deliver prototypes that is the main cause of friction between the aircraft and electrical industries. Unfortunately, the accessory manufacturer is always at a disadvantage in this respect; he is usually allotted a fixed span of time which presupposes no technical difficulties during development and after supplying his first, usually tentative, outline, is forever more limited in space allocation. Clearly the same argument applies to the development of the prototype aircraft, but, whereas there is some justification for delaying an aircraft programme to incorporate a major improvement to the aircraft performance, it is difficult, and usually impossible, to justify any delay to incorporate a change to an accessory, however vital the change may be to the accessory itself.

It could be argued that the electrical industry has been slow to recognise the special difficulties involved in creating new designs, making prototypes and developing reliable equipment, in the very short time demanded by the Industry. The difficulty has been the accurate forecasting of the long term demands of the Aircraft Industry both from the quantity angle and particularly as regards future electrical loads, which determine the size of much of the equipment. So that having doubled their facilities one year, the electrical industry must again double up the next year. But they can have little knowledge of the position in three to four years.

It is pleasing to note that the Ministry of Supply, and particularly the electrical and engine accessory development divisions, have taken longer term decisions on certain types of equipment with a view to giving equipment designers more adequate time for development of reliable apparatus. Admittedly they have not had an easy task, bearing in mind the necessity, now very apparent, for standardisation of system voltage, and many other features, with our friends across the Atlantic.

Even with this foresight, due to a change in the world situation, the industry is faced with developing and supplying complete generating and utilisation equipment for a new system voltage in less than two years from the start of design. It will be done, but it will be obvious that with this time limitation, the long term "x" of 1,000 hours will not be possible immediately but, as with the engine, the initial maintenance period will be less.

So far as the authors' firms are concerned, and they believe that they can speak for other electrical equipment suppliers in this matter, there has been a constant increase in development facilities over the past five years.

It is recognised that the laboratory testing of prototype electrical equipment, under certain assimilated aircraft conditions, constitutes the best method of eliminating the major snags in any piece of equipment in the quickest time. It must be obvious, however, that for the moment the aircraft remains the final test bed. Whether it will be possible to develop completely trouble-free apparatus in the laboratory in the future is problematical. It would certainly be somewhat easier if air-

craft designers were able to give some reasonable indication of conditions obtaining in flight—vibration, for example, is too often very much of an unknown and, without the data, how can the electrical engineer attempt to assimilate vibration in his tests? It is of interest to note that certain pieces of equipment which have given little or no trouble during the past 10 years, will not meet the present vibration specification of the R.A.E. (Tech. Note V.I.B.13) unless mounted on shock absorbers. Thus, the equipment is increased in weight and complication to cope with a specification requirement which, although based on actual vibration figures of the worst of many tested, unfairly penalises the best, or even the average.

In order to speed up development programmes, the electrical industry requires increased help from material suppliers. The somewhat small quantities of special and approved material required by the aircraft electrical equipment manufacturer during normal times, is often of nuisance-value only to the material supplier with his already heavy commitments with industry. The time delay between the testing of new materials and their availability, even in small quantities, is too great and, at times, has delayed the introduction of major improvements to equipment generally.

Nevertheless, much has been achieved in the increase of serviceability periods, both on military and civil aircraft equipment and the major steps which are being taken are outlined later.

3. GENERAL CONSIDERATION OF THE MOST RELIABLE SYSTEM

3.1. Speed of Electrical Machines

Since all aircraft electrical generating plant and a majority of the utilisation equipment incorporates a rotating machine of one type or other, consider first the ideal or optimum speed of drive for generators and of operation for ancillary equipment.

To the electrical engineer, the higher the speed of operation of a generator, the lower, in general, will be the weight of the machine. But with the present practice of driving generators directly by prime movers of variable speed, or through fixed ratio gearboxes, the designer cannot make use of increased speed, since for an input speed range of 3.5:1, he must design his machine to give its full output at the low speed of

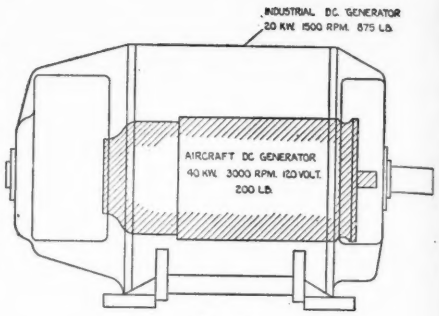

Fig. 4.
Comparison of D.C. generators.

2,800 r.p.m., giving a maximum generator speed of 10,000 r.p.m.

Since turbines mostly operate at a speed near to their maximum, it will be seen that such an arrangement gives neither the minimum weight nor the most reliable machine, as the top speed may be too high for maximum life of bearings, brushes, and so on.

Again it is extremely difficult to design D.C. machines to give satisfactory commutation over a wide speed range and regulation equipment for this range becomes heavier and more complicated.

The effect of speed on motors has already been shown in Fig. 2. With D.C. generators, industrial machines run at considerably lower speeds than the equivalent aircraft machines. Fig. 4 shows a comparison between an aircraft 40 kw. 3,000 r.p.m. generator and an industrial 20 kw. 1,500 r.p.m. machine. These machines would be comparable if the output of the industrial machine could be doubled with speed. Theoretically this should be so but in practice it is not possible. The effect of speed is illustrated in Fig. 5. The lower curve shows a typical load/voltage characteristic for a generator operating at 3,000 r.p.m. and at constant full load field current. For the same field current and twice the speed, the no load voltage would be doubled and the characteristic curve would follow the middle curve. At this speed, with the full load field current, the output has been increased in the ratio 70/30 by virtue of an increase in voltage. Provided that the armature could be wound to suit and a larger commutator fitted, this increased output could be achieved at the original 30 volts. By running at 9,750 r.p.m., the same generator would give the same current output at 120 volts,

i.e. an increase in output of four times—assuming that the machine could be operated continuously at 9,750 r.p.m.

In order to operate over the speed range shown in Fig. 5, the field current at higher speeds must be reduced to keep the voltage down. Unfortunately, the armature field (or armature reaction) is dependent only on load, so that even at the high speeds the main field must be kept above a certain safe minimum, with the result that more field copper is required. As speed ranges increase beyond the 2/1 range, additional special field windings have to be added to neutralise the armature field.

Figure 6 shows the comparison between the power-weight ratios of D.C. generators designed for minimum speeds of 2,800 r.p.m. and 8,000 r.p.m.

The electrical engineer would obviously like a constant, or reasonably constant, speed drive for his D.C. machine. It would become an essential of a constant frequency A.C. system, which will be described later. For the time being, therefore, some review of the actual speed range required would seem desirable.

Bearings and commutator problems alone limit the speed of intermittently rated D.C. motors. It can be shown that from the weight angle, it pays to operate the motors of geared units at high speed even though the gearbox ratio is higher and thus its weight is increased.

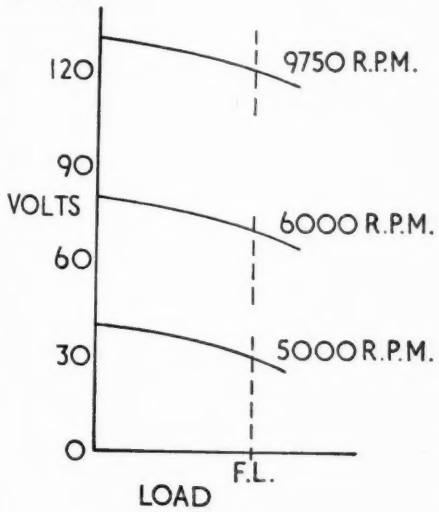

Fig. 5.
Characteristics of D.C. generator.

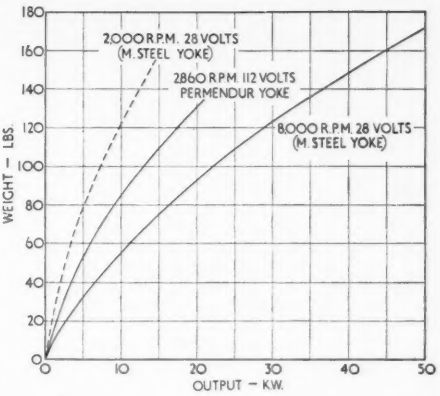

Fig. 6.
D.C. generator weights. 8,000 r.p.m. blast cooled at 50,000 ft. altitude; 28 volts output-interpole machine and 112 volts.

3.2. Voltage

Most present-day aircraft operate with 28 volt D.C. systems. While increased voltages, 112 is the figure for many new aircraft, certainly reduce considerably the overall weight of the equipment and cables, it cannot be said that any increase in reliability results. Certainly commutator problems are increased, the design of small commutators with the increased number of bars required for 112 volts being a difficult proposition. For the operation of small actuators and other equipment a 28 volt supply has to be retained. Switchgear and other protective gear is rather more complicated when designed for the higher voltage, and as yet, there is little service experience of this when operating at high altitude.

3.3. Alternating Current

An alternating current supply at, say, 208 volts would definitely result in reduced weight and much increased reliability for most types of equipment.

Apart from limitation of bearings, alternators can be operated at higher speeds than D.C. generators and their power-weight ratio at like speeds is higher.

A.C. squirrel-cage motors dispense with commutators and brushgear and are extremely reliable.

The reduction in weight and the increased reliability of A.C. systems has been dealt with in so many papers in the past that there is no point in repeating the whole story in

this paper. Suffice it to say that its non-introduction, due to the absence of satisfactory constant-speed drives, or independent constant-speed prime movers, is much regretted by the aircraft electrical engineer.

A rectified A.C. system goes some way towards making use of the many advantages associated with the alternator as a generator of electricity. In such a system metal rectifiers are used to produce direct current for all, or part, of the utilisation apparatus. Heating and other non-frequency-conscious loads can be supplied directly with alternating current but all motors on the system must remain on direct current, since the speed and therefore the power of A.C. motors of the non-commutator type depend upon the frequency of the supply, which itself varies with engine speed on present-day systems.

Rectified A.C. systems for particular applications can show a weight advantage, and there are already a number of aircraft using this system which are in, or about to go into, service. This is a contribution towards increased serviceability so far as the generator is concerned. Little flight experience has been obtained as yet with the rectifier.

4. STEPS TOWARDS INCREASED SERVICEABILITY

4.1. The electrical machine

It will now be as well to review the electrical machine, explore its reliability and indicate what progress is being made to improve is reliability and reduce its weight.

Briefly every machine consists of three main components, the armature or rotor, the stator, and the end frames carrying the bearings. In addition, all D.C. generators and motors and some A.C. generators require an additional component—brushgear.

Both the rotor and the stator contain the active materials of the machine and these are invariably iron and copper (or aluminium in some squirrel-cage windings).

The development of better techniques in the employment of these materials probably receives more impetus from industrial applications than from aircraft, since a reduction in the weight of iron and copper used leads to a cheaper machine. Naturally in aircraft applications it is usual to load the iron and copper to a greater extent and to operate at higher maximum temperatures.

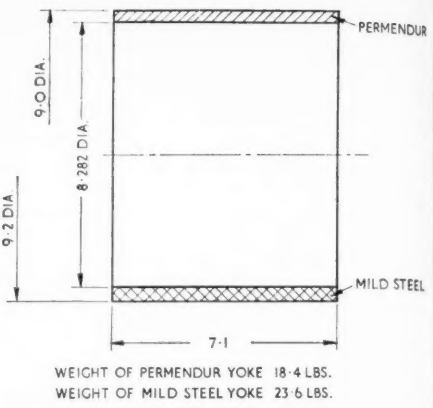

Fig. 7.
Comparison of 15 kw. generator yokes in different materials.

But industrial electrical engineers, being price-conscious, have not attempted to make use of several new magnetic alloys, namely, the 35 per cent. and 50 per cent. cobalt-iron alloys, which do show marked advantages as weight-reducing materials because of their high permeability figures (Figs. 7 and 8). These materials are somewhat brittle and care is necessary in the assembly of lamination packs in these materials. Their main drawbacks are very high cost and the present shortage of cobalt, which may prevent its general use for aircraft machines. It will be interesting to hear views on how much the Industry is prepared to pay for weight reduction.

For example, if by the use of a costly material, such as Permendur, a saving of one lb. is effected, then according to the leaflet published by the Weight Control Panel of the S.B.A.C., it should pay an aircraft constructor to use the lightweight component even if he is charged up to £35 per unit more than the price of the heavier unit.

So far a small number of aircraft generators and motors using Permendur yokes have been made and are on test. In some cases, pole pieces are also made from rolled sheet of this material.

Improvements in hydrogen annealing techniques can bring about some improvements generally in present grades of silicon iron, but it is perhaps unfortunate that the rotating machine cannot make use of the directional properties of Hypersil, Crystalloy, and other cold rolled directional sheet material, which

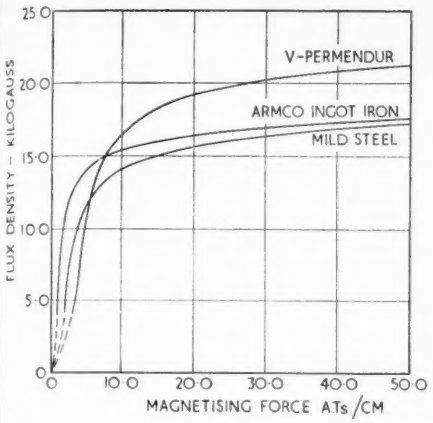

Fig. 8.
Magnetisation curves of various yoke materials.

is now widely used to reduce the weight of aircraft static transformers.

The effect of increased temperature usually has no effect on the life of the iron and copper, but it does have a marked effect on the insulating materials used. The breakdown of insulation is most probably due to a continuous process of oxidation of the varnishes and enamel used in the impregnation. This oxidation is accelerated by higher temperatures, although the exact relationships between "life" and operating temperature do not permit exact calculation. Industrially the electrical industry is only interested in new insulating materials and varnishes on a cost basis and new materials would only be considered if the application resulted in a lower selling price per h.p. or kw. output. At present there is little difference between insulation practice between aircraft machines and industrial machines, because under the pressure of war development it has been necessary to use the best insulating methods available at the time.

Until recently, the insulation materials available have not set a limit to the maximum temperature at which the machine can operate. But with the present tendency to eliminate soft solder from the armature of aircraft electrical machines and the possibility of further increases in maximum temperature which will then be possible, insulating materials, and particularly varnishes, may become the limiting factor.

It is bad practice to mix Class B inorganic insulation materials and an organic-based varnish in any one machine, and the need for a varnish to withstand 170 to 200°C. is now being felt.

The silicone products should one day provide an answer to this problem. Their use in Great Britain, without doubt, has been retarded by the fact that until recently no real attempt had been made to manufacture silicone products in this country. The cost has also been high but no doubt this will fall when production on a reasonable basis has been established.

New varnishes will bring lighter machines and longer ultimate life of armatures, but the authors have no knowledge of premature failure of machines through ageing failure of insulating materials.

Searching through the records of a number of different types of machines, the authors have only been able to find one machine which has reached the ultimate life of the insulation and this was on a starter motor estimated to have had 4,000 hours flying life. This particular machine was of a very old design using an inferior type of insulation and impregnation compared with modern practice.

The basic components of a D.C. machine are as follows.

Rotor

The main improvements foreseen are:

(*a*) The retention of conductors in slots at higher speeds and temperatures. This involves the elimination of soft solders from banding wires and probably the use of solid bands and possibly the use of enclosed or semi-enclosed slots.

(*b*) Improvements in the design of commutators for higher speeds and temperatures. This involves the use of better materials, the elimination of soft solder from commutator connectors by the substitution of brazing or welding methods (Fig. 9).

(*c*) Improvement in insulation materials to withstand higher temperatures. This involves the need for varnishes and other insulating materials for higher temperature, *i.e.* silicones or some other inorganic material.

Stator

The stator, which constitutes the field system of a D.C. machine and carries the main current for most aircraft alternators and A.C. motors, is obviously the least troublesome part of an electrical machine.

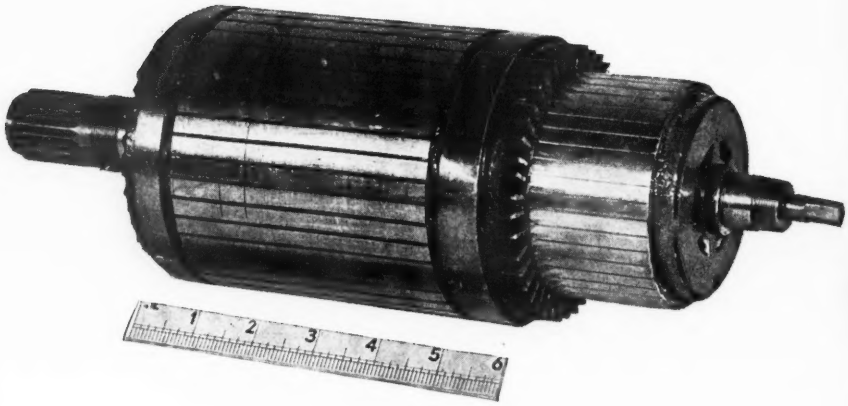

Fig. 9.
Typical armature for high temperature operation.

Insulation improvements would also be applied to the stator of a machine, but the most marked stator changes are involved in the basic design of a D.C. machine and the necessity of increasing the rating and improving the commutation over wide changes in speed and load.

Most D.C. generators of the future will carry both interpoles and their windings and also pole face windings. This makes the modern stator of rather more complicated construction than hitherto, but dividends should be paid in the increased life of brushes and commutators.

All starter motors will be compounded to reduce the no load speed of the machine on the higher voltages now being applied by certain types of ground trolleys.

Brushgear

The elimination of brushes carrying main current and brushgear would be an important factor towards solving several problems. Firstly, as mentioned earlier, commutation of D.C. machines over wide speed and load changes presents a great problem in itself, and weight penalties in the shape of additional interpole and pole face windings have to be faced. Secondly, there is still the high altitude brush wear problem which, although reduced by the use of impregnated brushes, is by no means solved and too frequent brush changes will be necessary when long periods of operation at 40,000 to 50,000 feet are encountered.

Considerable variations can, and often do, occur between the performance of two sets of brushes of the same grade. These changes are not due to variations in the composition of the brush, but mainly to changes in the brush bedding, the commutator skin, spring pressure, vibration, and so on.

Admittedly, although the A.C. induction motor dispenses with brushes completely, the current type of alternator retains brushes which carry the field current only to the field windings. This duty is much less onerous than the main D.C. brush problem, since the brush temperature, current density, and so on, are much reduced.

Mechanical framework (with bearings)

Here again industrial practice aims at low price and as a result differs vastly from aircraft practice. It is in the application of lightweight materials that the Aircraft Industry is far in advance of the electrical industry and it is in this part of the electrical machine where a far greater collaboration between the two industries would be advantageous.

With large electric actuators which are now finding some favour for undercarriage retraction, and so on, the mechanical framework quite often forms an important part of the aircraft structure and has to be stressed accordingly. In some cases the electrical contractor merely supplies the motor to operate through the aircraft constructor's gearing and screw and nut mechanism. There

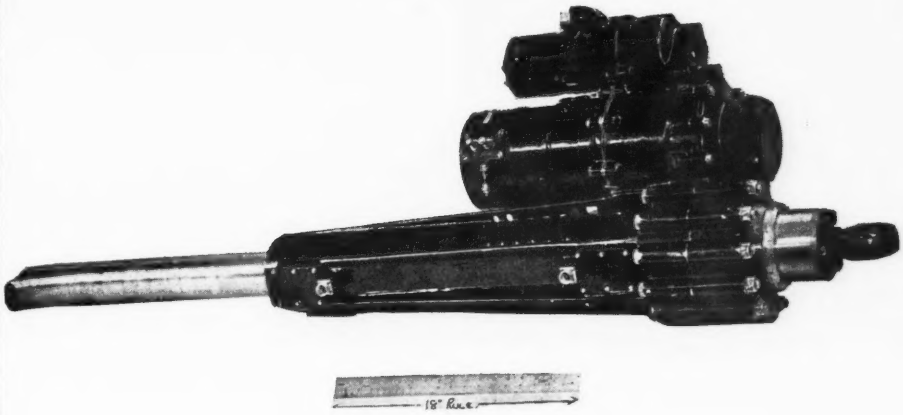

Fig. 10(*a*).
Large linear actuator, with high efficiency screw.

are certain virtues in either arrangement from the aircraft angle, but the former very often leads to earlier completion of development, since the designer is employing motor, gearing and screw of known efficiency and can predict more easily the performance of the complete unit. He can also test the unit as a whole on his premises. Servicing is also very much eased by the unhooking of two shackles and the withdrawing of a plug from a socket.

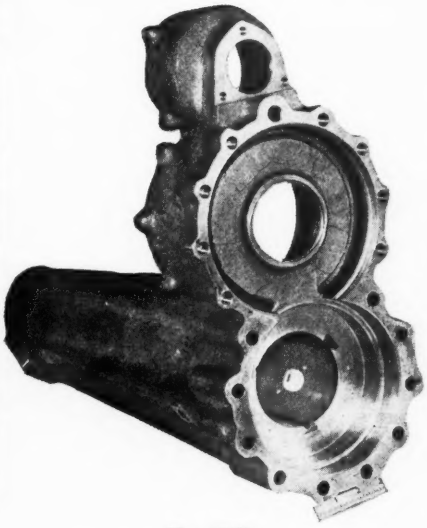

Fig. 10(*b*).
Ram housing for large actuator.

The design of large self-contained electrical actuators has involved many problems and has certainly brought about new foundry techniques in connection with the large light-alloy castings used on these units (Figs. 10(*a*) and 10(*b*)).

The increased use of light alloys and particularly magnesium alloys, must be encouraged for the end frames of all machines. Better anti-corrosion treatment for magnesium alloys would be helpful.

Statistics will show that more electrical machine failures can be attributed to ball bearings than to any other cause.

Certainly it is the authors' view that development of ball bearings for aircraft components in Great Britain has not reached the advanced state of development of many of the components. This is mainly due to lack of interest in the small quantities involved, absence of development facilities, or both, by the leading ball bearing manufacturers.

Whether the ball bearing manufacturers have been encouraged by Government-sponsored development contracts to produce the special or precision bearings required by the aircraft accessory firms is not known, but there has been a complete inability to supply such bearings. Shielded and sealed types of bearings, which are necessary for adequate grease retention, are not available in the sizes required although such types are available in the United States of America.

In point of fact, it has been found necessary to use American-made bearings, with the

dollar expenditure involved, in order to meet some of the requirements. Too often has the electrical engineer had to accept standard bearings or nothing. Admittedly mistakes have been made in the application and lubrication of bearings and no doubt this has caused the bearing manufacturers to adopt an attitude which is usually expressed—"The bearing is satisfactory but the lubrication or the application is wrong."

It is agreed that no available lubricant is entirely satisfactory over the full operating temperature range. Hence the demand for seals or other grease-retaining devices.

In industrial practice a 2-pole 50 cycle induction motor running at 3,000 r.p.m. gives an almost unlimited bearing life—often without attention. Spinning motors running at 6,000 r.p.m. give a bearing life of 40,000 to 50,000 hours. It should be noted, however, that the only rotating parts are the motor armature and a form of metal cup which is either part of, or solidly connected to, the motor shaft so that there are no alignment problems. Woodworking machines running at speeds as high as 30,000 r.p.m. give a bearing life of from 1,500 to 2,000 hours. Recent improvements in woodworking machinery are expected to increase the bearing life to 5,000 or 6,000 hours. In aircraft it is difficult to maintain a bearing life of 1,000 hours for an engine-driven generator running at 10,000 r.p.m., which is an indication of how severe is the duty in the aircraft application.

Fortunately there has been an awakening to the needs of the Aircraft Industry by several firms within recent months and the authors feel confident that improved bearings will result. What is really wanted is the establishment of a range of ball and roller bearings made to closer limits and with better finish in the tracks and cages. The ball races should be available with or without grease seals.

The grease manufacturers have been alive to these requirements and considerable progress has been made in the improvement of their products. But much remains to be done if the $-70°C.$ conditions laid down for many components are to be met. Extension at the higher end of the temperature range is also an urgent requirement in view of the higher temperatures expected in the future. The silicones greases come to mind and further development of this product may bring an answer to the problem. Alternatively, engine oil supply to, say, generator bearings might have consideration.

Plain bearings of sintered materials may have further application on certain types of machines.

Summing up the progress necessary to improve the reliability of the electrical machine, it can be said:—

(1) A.C. generation and utilisation should be the goal, bringing with it as it does more robust generators and motors with fewer parts and no commutators. A.C. generation at constant frequency could bring about the elimination of many of the inverters now necessary.

(2) A serious attempt to improve ball bearings and their lubrication, with the possibility of employing other types of bearings.

(3) Weight reduction by use of magnesium alloys for frames, new magnetic materials for yokes and poles.

(4) Better commutators suitable for higher speeds and temperatures. The use of copper alloyed with silver or chrome to increase its hardness at higher temperatures is a feature of this development.

(5) Extended work on the altitude brush wear problem with a view to increasing brush life.

(6) Investigation into methods of cooling electrical machines at high altitude.

4.2. Control and protection equipment

The main generating plant of any aeroplane is so designed that the supply of current to all services is adequate even if, through engine or generator failure, part of the normal supply is no longer available. For example, if a four-engined aircraft can maintain normal flight on two engines, then the generators associated with two engines only must be capable of providing the load.

It is important, therefore, that in the event of any fault whatsoever occurring in one generator or its circuit, the offending equipment should be isolated from the main bus bars, permitting the other generators to continue supplying power to the system.

The control and protection equipment of an aircraft electrical system is of vital importance since, with the increase in loadings on many projected aircraft, short circuit currents higher than 10,000 amps. can feed into a fault on a generator circuit.

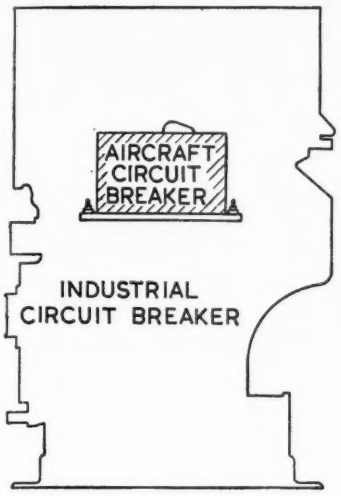

Fig. 11.
High speed circuit breaker.

In industrial applications the use of automatic control gear has developed into a fine art and many almost magical examples of automatic control are well known. In aircraft there are applications for automatic control but in the interests of safety it is always best to aim at the simplest form of control. The old method of direct switching with fuse protection has much to be said for it for simplicity, but as power systems become more complex, fuse discrimination becomes more difficult, or impossible, and other methods must be adopted.

In the past, no 100 per cent. protection scheme has been available and a compromise has been necessary. For the future, on military aircraft at any rate, complete protection against all faults except those of the main bus bar is hoped for, including discriminating over-voltage protection. On military aircraft, cable and other faults can arise through enemy gunfire but it is questionable whether, with efficient wiring systems, it is necessary to complicate the civil transport aircraft with as complete a protection system as is necessary for military duty.

During the latter part of the 1939-45 War, circuit breakers were developed for 24 volt systems and these were used as contactors for switching equipment on and off, as well as protective devices. On large output systems this arrangement is not satisfactory since in order to make the circuit breaker handle the large fault currents that might occur, it has to open very quickly and this means a heavy contact pressure. It is better to close the circuit breaker against a heavy contact pressure by hand and to leave it closed and to perform normal switching functions with a separate solenoid-operated contactor. By this means the circuit breaker contacts are maintained in good condition and have a better chance of clearing a serious fault, should it occur. This practice is essential on 112 volt systems in view of the difficulties in rupturing heavy fault currents at altitude.

It is in the development of aircraft switchgear that the electrical engineer has had to explore entirely new methods. In industrial practice there are no space or weight limitations and circuit breaker contacts can be immersed in oil and large arc barriers can be provided. Circuit breakers in industry are not used as contactors and large power station circuit breakers are usually examined at least once a year, even if they have never been operated. A thorough examination is always made after a circuit breaker has cleared a large fault current.

Switchgear development takes a long time, particularly when a change in system voltage occurs, since basic data for lightweight equipment for the new voltage has to be established before design work can begin.

Much has been done, rather belatedly, on the development of new high speed, manually-operated circuit breakers for aircraft, both for 28 volt and 120 volt systems (Fig. 11). A range of circuit breakers with thermal trips and single and reversing contactors also exist for 28 volt and 112 volt auxiliary circuits.

The introduction of the polarised differential relay in place of the old type of reverse current relay, has done much to improve the reliability of generator circuits. This relay operates the contactor which puts the generator on to the bus bars and is designed so that with a 28 volt system it operates when the generator voltage exceeds the line voltage by 0.5 of a volt (Fig. 12).

Improvements in switchgear generally are mainly related to the use of better contact materials more readily able to carry heavy current with minimum voltage drop and arc resisting properties, improved arc chutes and blow-out devices, the availability of more consistent bi-metallic strips for thermal trips and a general tightening up of manufacture

and inspection of small switch mechanisms of intricate design.

Much remains to be done in these directions in order to satisfy completely, future aircraft requirements.

4.3. Lighting and heating

Filament lamps for use in aircraft on 24 volt systems have been developed to a high degree of reliability. On 110 volt systems the smaller section wire required in the filament will reduce considerably the robustness of this part and it is unlikely that 110 volts will be used for general lighting. It may be desirable to use 110 volts on high power lamps, such as landing lamps, where the filament will still be fairly robust. Modern fluorescent lamps give a very much higher efficiency in lumens per watt, but are inherently heavy in construction.. Assuming suitable power supplies are available, the weight of a fluorescent lamp installation is likely to be greater than the weight of the equivalent number of filament lamps. In other cases it may be necessary to provide motor generator sets to provide the correct power supply for the fluorescent tubes.

In general, little thought has been put into the development of fittings either for filament lamps or fluorescent tubes. Aircraft lighting installations could be improved but since the lighting installation is so intimately connected with the general furnishings it will need closer collaboration between the aircraft designer and lighting engineer than exists at present.

For heating purposes electric power offers many advantages and for purposes such as cooking, has no equal for aircraft applications. Where electric power for heating is required in large quantities for such applications as de-icing, the modern tendency is to use A.C. power at 208 volts, either from separate generators installed solely for the purpose, or from the main generators suitably increased in power output for the purpose. Such arrangements are not always the most economic since there are often other sources of heat already available which can be used for de-icing. For propeller de-icing electrical power is the most convenient and the most successful method so far employed and special generators installed in the propeller hub have been developed for the purpose or, alternatively, power from the aircraft normal supply can be fed in through sliprings (Fig. 13).

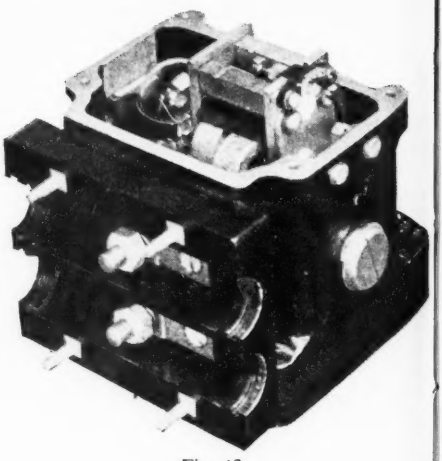

Fig. 12.
Differential cut-out.

4.4. Wiring and wiring terminations

Improvements in aircraft cables have taken place during the past year or two. One such improvement is the introduction of the Pren series of cables in which the conductor is covered with a woven glass braid over which is extruded a Neoprene dielectric. Such cables will operate at higher current densities than hitherto, but their weight, based on voltage drop figures, is disappointing. P.T.F.E.-covered cable for extremely high temperature use is now being introduced.

The introduction of aluminium cored cables has not yet been possible, mainly because the development of the crimping technique has not yet been completed. Every effort to speed up this work is necessary in the interests of minimum weight and economy of copper.

The position regarding cable terminations generally is chaotic. The S.B.A.C. connector, introduced after considerable deliberation between aircraft constructors, now fails to find favour with many of them. From the angle of standardisation, the unfortunate electrical designer is up against it, since he is now called upon to design his equipment to suit two or three types of plugs and sockets, as well as the S.B.A.C. connector and the approved M.O.S. terminal block.

Solderless connectors have come to stay and this is a noticeable improvement, eliminating as it does the human element so often responsible for failure when soldered connectors are employed.

4.5. Electronics

The electronic valve is undoubtedly the most useful tool ever presented to the electrical engineer and has introduced an entirely new field of engineering under the general title of "Electronics." The great danger in applying electronic apparatus is that of over-enthusiasm. Electronic valves can perform certain functions that cannot be performed by any other means, they can perform certain other functions better than other means and these are the only correct applications for valves. In these "correct" applications valves have proved to be no less reliable than other electrical apparatus. Over-enthusiasm has led to the use of valves for functions that can be performed better by other apparatus, and failures in such applications have led to a general distrust in the use of valves. Nowadays it is impossible to study and practice any form of engineering without coming across electronic apparatus sooner or later—usually such apparatus is performing some vital function. Needless to say electronic apparatus has found a place in aircraft equipment, not only in radio and radar, and in common with all other equipment applied to aircraft has been compressed in size and loaded beyond normal limits. This has led to the usual difficulties and failures, but a vast amount of experience with miniature electronic components has been accumulated and is now available for the good of the industry. It is because of these failures and because the mechanism and operation of the valve is not fully understood by aircraft engineers (and, incidentally, many electrical engineers), that the "black box" is regarded with some suspicion and distrust.

The development of valves during the 1939-45 War in many cases suffered from the fact that such vast quantities of valves were required that production had to be spread among many valve manufacturers. Quite often the firm that developed a particular type of valve did not produce it, with the result that the specifications had to be modified or eased, to enable different manufacturing techniques to be employed.

It says much for the valve industry that electronic apparatus performed as well as it did during the last war. Fortunately, steps are now being taken to manufacture and develop a range of more rugged valves. In addition, improvements are being made to existing types of valves and closer specification limits are being applied. This action will bring benefit both to the users and designers of electronic equipment. It is hoped that once a high standard has been achieved it will never be relaxed.

Nevertheless, designers of electronic apparatus will always recommend that the use of valves should be avoided wherever it is possible to use other methods equally as effective. For example, the magnetic

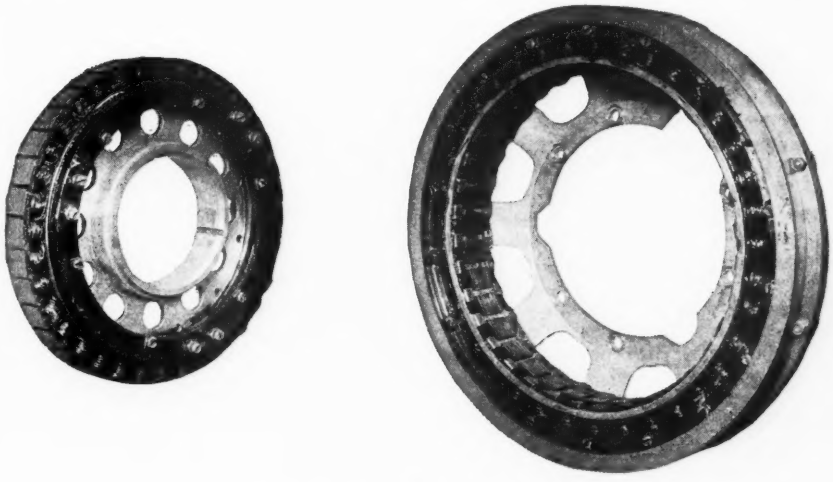

Fig. 13.
Typical hub-generator for propeller de-icing set.

amplifier is a more robust piece of apparatus which in some applications can be used in place of valve circuits. It can also be used to replace relays in certain circuits, provided that there is an A.C. supply available. Magnetic amplifiers and electronic valves will undoubtedly be used individually, or in combination, with one other in many aircraft electronic units of the future.

4.6. Some typical advances in development

Some notable advances in the development of electrical equipment have taken place during the past ten years.

During that period, for example, generator capacities have increased from one kilowatt to 40 kilowatts D.C. and alternators of about the same capacity are now available.

Blast cooling for electrical generators was rather belatedly introduced at the beginning of the Second World War. Thus a 50 per cent. increase in output of a generator became possible with no increase in weight. The type K generator rated at one kw. became the type KX of 1.5 kilowatts by blowing air over the commutator. Later this machine was uprated to the type 02—3 kilowatt, this being possible by the introduction of interpoles and by blowing the cooling air through the machine. These changes were the result of war-time development and it was very necessary to make the minimum amount of alterations to the machine so that production would not suffer. Therefore this would not represent the best possible design of 3 kw. D.C. generator. This generator weighs 35 lb. and today there is a 6 kilowatt machine weighing less than 55 lb. and a 15 kilowatt machine weighing 105 lb. for a lower minimum speed—the latter giving its output at 50,000 feet compared with 40,000 feet for the 6 kilowatt generator. These weights refer to direct current machines. Aircraft alternators have had blast cooling since their use on aircraft began, but the power-weight ratio is being constantly increased and there is now a 40 kva. machine weighing only 62 lb.

These weight reductions have to be brought about with little or no reduction in efficiency. Obviously fuel is used in driving continuously running auxiliaries and it is important that the Aircraft Industry should compare electrical component weights on the weight and efficiency basis. In other words, a penalty based on the losses of the machine should be added to the actual weight when assessing the gross weight which is being carried.

Again with actuators, very big strides have been made to reduce weight and increase the efficiency, mainly by the use of a re-circulating ball type screw and nut. Large actuators giving strokes up to 20 in. in 9 seconds with a loading of 25,000 lb. are now available.

Small electrical actuators applied for control purposes on engines and power plants, after a somewhat difficult teething period largely due to an ignorance of the operating conditions, in many instances have now attained 1,000 hours' life before maintenance.

As mentioned earlier, the modern magneto when fully developed in collaboration with the airline operators, has become an extremely reliable piece of apparatus. This despite the big increase in sparking plug voltages which are necessary for many present-day high boost engines. It is an indisputable fact that engine development has never been held up for want of magnetos and this despite the more onerous requirements which have been laid down.

The achievement of the aircraft electrical industry in the field of electric starters is such that many aircraft designers continue to press for the retention of this form of starting for large turbines.

Figure 14 shows a 112 volt 35 h.p. starter, which will also operate from an internal 120 volt 40 ampere-hour battery, and which weighs only 55 lb.

These examples are a few of the many improvements covering the complete aircraft electrical engineering field which have been brought about by intensive development during recent years.

4.7. Application and installation

It is in the application of electrical power to aircraft and the installation of the equipment on the aeroplane, that a closer collaboration between the aircraft designer and the electrical designer is most necessary. There has been a noticeable improvement in this liaison during the past few years and the chief aircraft designer now invariably employs staff with specialised electrical knowledge to advise him on circuit layout and to prepare specifications of equipment performance. Even so, many cases still occur where the performance requirements are scanty and much too vague. For example, the requirements of motors to drive hydraulic and other pumps are often so

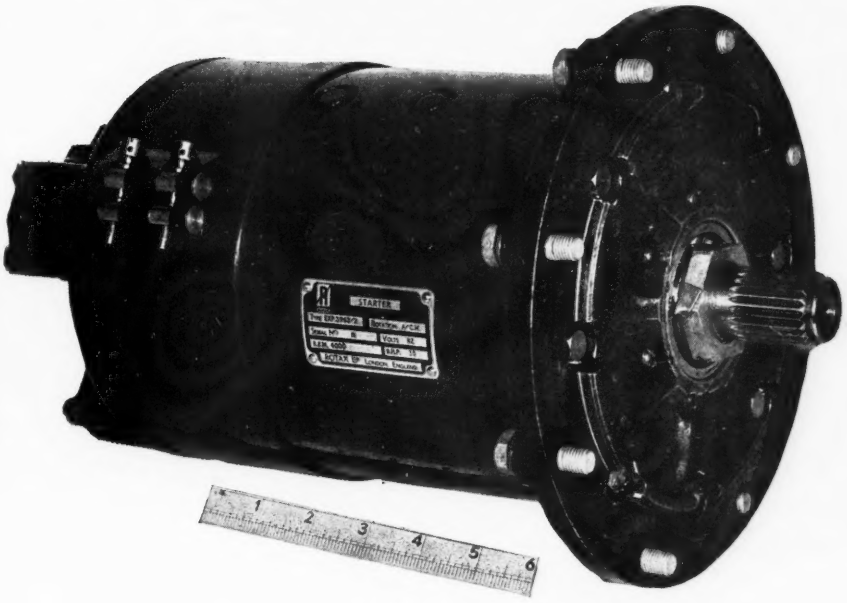

Fig. 14.
112 v. 35 h.p. starter motor for large turbines.

inadequately stated that the motor produced in prototype form is either too small or too large. Actuator specifications often fail to cater for torque increase in the mechanism which the actuator is driving, such increases being due to reduced temperature and other causes.

The second point for serious consideration by the aircraft designer is the allowance initially of adequate space in his layout for the installation of the electrical component. Very often designs become unreliable because the electrical designer is asked to design a 10 h.p. motor for installation in a space adequate for a 5 h.p. motor. Engine designers should note this point. Turbines, more often than not, are designed without adequate consideration being given to the space required for the starter and the generator.

Another important point concerns the vexed question of voltage drop in the various circuits of an electrical installation. It has already been stated that the design of utilisation equipment to operate over a wide voltage range is an embarrassment to the designer. In these days of constant voltage supplies on aircraft, it is considered that no longer should equipment have to operate from the battery of the system. Ground testing should be possible from a regulated generator supply on the ground. Minimum voltage drop from 28 volts should be accomplished by careful consideration of cable sizes.

What often happens is that equipment is rejected as unserviceable because it will not operate on absurdly low voltages. In one case which can be quoted, apparatus designed for 18 to 28 volt operation was stated to be faulty because it would not run with a voltage of 14 across its terminals. This condition was brought about by the use of a discharged battery, plus a cable of half the necessary cross-sectional area.

Closer liaison between the electrical and the aircraft industries will lead to a better understanding by both industries of one another's difficulties, and will eliminate many cases in which lack of serviceability can be avoided or minimised.

While it is not the wish of the authors to criticise the users of electrical equipment, the airline operators, or R.A.F. personnel, it is of importance to record in this paper the necessity for refraining from interfering with equipment at too frequent intervals. The

popular term for this is "finger trouble" and it can lead to damage and reduce the life of apparatus which would normally go on running satisfactorily for long periods.

Inspection staffs of a number of operators, and this also applies in some measure to the R.A.F., have to sign off aircraft for operational flights from home and overseas bases, and there is evidence that there are too many routine checks on electrical components which do more harm than good.

For example, the regular checking of magneto contact gaps by feeler gauges, both upsets the bedding and very often introduces oil or other contaminants on to the contacts. Such treatment can lead to sparking at the contacts and intermittent operation of the magneto.

Again, with electrical machines, too frequent inspection of brushes by removing them leads to a spoiling of the bedding and the damaging of brush springs.

The sealing of equipment would seem to be the only answer. With sealed equipment no maintenance checks would be possible until the regular scheduled hours for the equipment had been completed.

5. CONCLUSIONS

The authors consider that aircraft electrical equipment design has advanced technically as far as the associated aircraft or its engine.

The limitation of present-day 24 volt systems, as increased power is demanded, is leading to higher voltage systems which are already installed on the Hermes, Ambassador and S.R.45 aircraft. Such systems will incorporate D.C. generators or alternators with rectifiers and the merits of these systems will be apparent only after prolonged service life. Both systems retain a substantial 24 volt supply, which is unfortunate, but necessary, until more equipment is available for the higher voltage supply. It is obviously important, if not to eliminate, to reduce, the 24 volt supply to a minimum.

With either of these systems, D.C. utilisation is still used and an all-A.C. system must be developed for the large civil aircraft of the future.

The possibility of obtaining light-weight and reliable constant-speed drives now looks more hopeful, the authors having in mind the work of Gerritsen, Beier and others. A specialist development firm in the industry now has an extensive programme of work in this direction.

Such drives may not reach the desired accuracy for parallel operation of alternators, but would show great advantages with D.C. generators. By reducing the generator speed range to a very narrow band it may be possible to save sufficient weight in the D.C. generators to compensate for the added weight of the gearbox.

The ultimate ideal installation would be the use of auxiliary generating plant. The equipment installed in the Shetland aircraft was electrically ideal, but the particular auxiliary engine used to drive the generators is suitable for operation only at low altitudes. If a small auxiliary turbine unit could be developed successfully, it should be possible to apply turbo-alternator construction techniques to aircraft alternators. This would mean developing a 2-pole 400 cycle alternator running at 24,000 r.p.m., which surely is not an impossible task. Such a system would utilise no D.C. machines at all and any small quantities of direct current required for, say, contactor coils, would be obtained by rectification from the A.C. power.

If an ideal A.C. system is realised, then machine design will be limited first by bearings and later (if bearings are improved) by insulation. By that time it should be possible to guarantee a life period and to operate on a replacement system. It would be economical to replace all the electrical machines after, say, 3,000 hours, if during that period no attention whatever were required.

More careful consideration is required for the general application of electrics to aircraft. It is not the authors' opinion that electric power is the only type of power that should be considered. When electric power shows obvious advantages, which is often the case, then it should be used and the exact requirements stated or determined as early as possible in the development of a new project. In order to gain more experience the electrical industry must undertake very thorough testing of all items under simulated flight conditions. Collaboration with the aircraft manufacturer is always preferable and if possible, flight testing. This will lead to expensive equipment and to a prolongation of the development period.

The electrical industry has much to learn from the Aircraft Industry about methods by which the development period can be reduced. The aircraft firm has the advantage of the glamour surrounding the new project and usually devotes its entire efforts into one

project at a time. The simultaneous development of a large variety of electrical items presents a very difficult problem for any factory, but it is a problem which must be solved in order to give satisfaction to the Aircraft Industry.

DISCUSSION

S. F. Follett (D.Inst.R.D., Ministry of Supply): He had been unable to trace the word "serviceability" in the Oxford Concise Dictionary, but the word "serviceableness" was defined as "suited for rough use or ordinary wear rather than for ornament." In the aircraft world, they were perhaps too familiar with the expression "unserviceability"; the authors' definition of "serviceability," in which they had grouped reliability, minimum weight and ease of maintenance, was hardly the converse of "unserviceability." He thought that the weight aspect should be omitted from their definition, and that they should define "serviceability" from the point of view of the ability of the equipment to withstand rough usage. Reduction of weight should be classified as performance.

In Section 2.2 of the paper the authors had referred to the difficulty experienced by electrical contractors in obtaining information from the Royal Air Force about their equipment. He hoped the situation would improve rapidly with the new policy the Air Ministry were adopting, of encouraging contractors to visit R.A.F. stations and investigate the performance of their equipment. Particulars of the arrangements could be obtained from the S.B.A.C.

He agreed that a piece of equipment should serve for 1,000 hours without needing maintenance; and he had the support of the users, the R.A.F., in the request that that should be so. The authors had suggested that aircraft designers might put forward reduced figures for life which would enable the performance to be improved to a small extent. Although he sympathised with that point of view, aircraft serviceability was also important and an aircraft which was often out of service because its accessories needed maintenance might be of less value than one of slightly less efficiency which was more serviceable because it had not to be maintained so frequently. He doubted whether the difference between 500 and 1,000 hours for the period "x," in terms of performance, was really significant; he did not believe that the design of electrical equipment for aircraft was so exact a science that they could design for lives of 500 or 1,000 hours.

It was essential that all types of equipment should be tested over long periods and that the testing should be done on a statistical basis, not in ones and twos; also, tests should be made on samples drawn from production, to check that the initial standards had not depreciated during production. Work was being done to determine operating conditions precisely; but until they were determined and suitable equipment provided, much useful information could be obtained by running "life" tests under normal laboratory conditions and by such desirable expedients as running the complete aircraft electrical system on the ground, driving the generators by means of small prime movers, testing the stability of the system under those conditions, the safety of the protective gear, and so on. He believed the authors would agree from recent experience that they had learned, and could learn, from such tests.

Flight tests would be necessary in the final stages, but they were expensive and lengthy, and it was necessary to ensure as far as possible that every possible doubt was taken out of the equipment before it was committed to the air.

As the authors' had pointed out, unless the aircraft designers gave the electrical contractors more time in which to complete their development work, they were unable to give the equipment adequate testing before installation. He was hopeful that the electrical specialists now employed by the aircraft firms would help the electrical contractors to obtain early information on what was required. As electrical equipment became more and more important in aircraft, even Chief Designers themselves might become electrically minded and able to set out the main requirements of a system in the early stages of their designs. The authors had said they could not consider delaying an accessory for the incorporation of a change, for possibly that would slow down the aircraft programme. He felt that that point

of view would gradually change. The equipment was becoming so important that the aircraft would not be able to fly without it; if it were unserviceable, the aircraft would not be allowed to take off.

He thought that A.C. generation and utilisation was a most desirable goal, but he assumed that the authors had in mind methods of providing the essential constant-speed drive without adding to the risk of unreliability, such as could be seen in some complicated devices and gear used abroad. The Ministry were fostering development work on constant-speed gears, and the Gerritsen gear, which had been mentioned, was one of the fruits of that work.

The Ministry were also trying to develop better ball bearings, not primarily for electrical generators, but for other applications in aircraft. Some excellent bearings were now being produced and he was watching those bearings for use in generators when available. Those bearings were made with great accuracy and the authors should be reminded that, if they were provided with high accuracy bearings, it was important to make quite sure that their designs were such that the performance of the bearings would not be spoiled by errors or by variations in the mechanical precision of their designs.

He agreed that more work should be done on the cooling of generators; it entailed the provision of extremely large plant, and the Ministry had such plant under way. The Royal Aircraft Establishment and the contractors were also working hard on brush wear investigation.

G. R. Edwards (Vickers-Armstrongs Ltd., *Fellow*): As Mr. Follett had indicated, aircraft designers, and particularly Chief and Assistant Chief Designers, were not electrically-minded.

Questions about equipment, how much to put in and whether to put it in at all, were largely settled by specialists, as had been indicated. It seemed that they could not escape having electrics in an aeroplane, because the users would insist on equipment which must have electric power to make it work, whether it be a radio set or a cooker or any such device. They had to decide what to install, where to put it and whether, having got it, they should consider the position in a large way and do away with other things.

There was no doubt that the improvement in serviceability which Mr. Woodall and Mr. Higgs had led them to believe had taken place was due almost entirely to the goading which the aircraft designers and their staffs had applied to the electrical industry. Far from not being electrically-minded, it looked as though, by coercion and help, the aircraft designers had made the electrical industry a little electrically-minded too !

Thus, the aircraft designers were aware that there were electrics in aeroplanes and that something should be done about the matter.

The authors had asked how much the Aircraft Industry were prepared to pay to make sure that equipment would be made lighter. They had quoted figures showing the relative costs of materials; the relative costs of a bar of steel and a bar of Permendur were about 1-10, but surely they were not seriously suggesting that the fantastic costs which were already imposed on the Aircraft Industry would be appreciably affected, whether steel or Permendur were used ? It was necessary to be engaged in the Aircraft Industry for some years before becoming accustomed to the fact that a piece of ash or something else which could be bought for about 9d. normally, would cost about £5 because it bore a rubber stamp somewhere; they became inured to the fact that things cost more when they were going into an aeroplane than when they were going into, say a vacuum cleaner. But even case-hardened people such as himself found it difficult to justify the cost of electrical equipment.

The authors wanted the R.A.F. to tell them what was the matter. But they might take a little more notice of the Industry, which had already told them.

There was the old bogey that they could not have high performance and serviceability at the same time, but the reasons why actuators, electric motors, and so on, went wrong had not really much to do with high performance. They went wrong because, for example, some operator had dropped a blob of solder where it should not be, or somebody had put wheels into the reduction gear, probably with the aid of a 7 lb. hammer. The trouble had nothing to do with the profundity of the design or with high performance; it was due to elementary factors of which sufficient notice was not taken.

Reference was made in the paper to the the virtues of A.C. generation, with rectification when D.C. was required.

He felt that D.C. would rapidly take precedence over A.C., which needed constant-

speed drive and automatic load sharing. They were concerned with the break-even point on weights and he felt sure that, when they added the other things which seemed to be essential, they would find that the break-even point would be considerably above 100,000 lb. all-up weight. The fact that some of his competitors were adopting A.C. cheered him considerably !

The modern aeroplane was capable of having nearly everything operated electrically. Was there any chance of applying to aeroplanes the sort of electric braking which had been applied to trams for many years ? There was a hydraulic system for the sole purpose of applying the brakes. To have a few more lengths of wire for putting the brakes on did not seem to be much of an extra hardship.

The electrical equipment industry had improved. The standard of design, particularly the mechanical design (which had been weak in the past), of electrical equipment of that vintage for which the authors of the paper had been responsible, was far and away ahead of anything they had seen before. It really did represent a positive step in the right direction.

It was right and proper to test everything extensively before it was installed in the aircraft, not merely as a piece of electrical equipment, but under the conditions in which it would operate. He endorsed the plea that it should be put into a rig with an undercarriage, or whatever aircraft equipment it had to work with, and be made to work thousands of times before it was installed in the aircraft. That meant that the electrical contractors had to supply the equipment even faster than ever, to give the users time to make the necessary ground tests.

C. G. A. Woodford (*Associate Fellow*): He was not at all sure that comparison with industrial or central station practice was worth while, since the aeronautical field had such special demands for different treatment; more progress technically, with added reliability, might have been achieved in recent years if more attempts had been made to conceive the aeroplane as an entity having its own electrical code of practice and requirements.

In particular he referred to a misplaced belief in the paralleling of generators (but not main engines), and the supposed need for elaborate protective devices, themselves a potential source of trouble if they existed, and trouble enough because they did not exist.

The situation reflected the need for a properly conceived overall technical policy. A hand-to-mouth, almost panic-ridden, series of haphazard developments had tended to disregard the advice of specialists who had given the matter the broad study that was needed, and they had been rushed from 24 volts D.C. to 208 volts A.C. and back to 112 volts D.C., leaving trails of promises and bad gaps in essential equipment. That might be serious, because no-one could say at present whether the new aircraft would be able to clear faults on 112 volts D.C. at high altitudes.

The 112 volt commutator was no less an evil because it was smaller—rather the reverse; and brushes must still be long in order to endure at altitude.

If the simple, robust, A.C. system, with much of its utilisation at variable speed, had been vigorously pursued and the essential 2- and 3-pole switchgear produced, they would not be asked to install cumbersome and vulnerable rectifiers, with a loss of one-third of the power distributed. He thought aircraft designers would be more satisfied with actuation in a reasonable overall time, than with a nice calculation of the rate of movement independent of engine speed, if maintenance-free equipment were thereby employed.

He believed that further efforts on constant-speed drives would be wasted, as much had already been wasted in Great Britain and elsewhere, because, like the rectifier, they wasted power, space, weight, maintenance and cost, at the expense of simplicity and reliability, and, as the authors had stated, they could not expect to govern close enough for synchronising alternators. They should take the more practical standpoint and agree that what was wanted most was the prime mover of 200 h.p. to provide the ancillary power, instead of other units to convert it; and they should proceed with due discretion. Why postulate alternators at 24,000 r.p.m. when they were trying hard to achieve reliability at 8,000-10,000 r.p.m. ? What manufacturer would rush at making a 2-pole alternator of 60 or 120 kva. for 24,000 r.p.m., and how would he get the cooling air through it at 50,000 ft. ? It would be better to associate the 8,000 r.p.m. alternator-cum-motor with a cabin blower of similar power and speed on each turbine engine and

to use the generator for running up the engine, as he had advocated elsewhere.

The subject was serviceability, and they should not forget that they were bound to retain a 24-volt installation with whatever higher power system was adopted. The extra low voltage equipment was at least well tried and proven for use within its power limitations. Why, in some new aircraft systems, were 24 volts being kept inside the pressure cabin and 112 volts outside?

They could, and should, do better in the performance and serviceability of electrical apparatus if they recognised that often in the Aircraft Industry the best for tomorrow had been the enemy of the good for today, and that when aircraft designers had the courage to sponsor new equipment concurrently with their new aircraft, some real improvement in service would result.

P. L. Cronbach (Handley Page Ltd., *Associate Fellow*): For the man in the aircraft firm the task of deciding on electrics was unenviable, for he could not be a specialist on a subject which varied as much as electrical generation and utilisation in an aircraft. The electrical man in the aircraft firm had the problem of assessing the specialists in sub-contracting firms and deciding whether or not they were right before they put the equipment into the aeroplane and flew it. An enormous amount of bench testing could be done, and yet equipment did go wrong in the aeroplanes.

One of the big gaps in the present testing arrangement was the lack of flight testing facilities outside the particular prototype which was being flight tested at any moment; so far as he was aware, there was no aircraft of suitable type available in the experimental establishments on which, when a really bad electrical problem arose, an electrical equipment could be tested to find out what was wrong.

There had been many trials in the development of new equipment in production aircraft, and the civil operators were bearing the full brunt of the development of post-war electrical equipment when it came to running it to death. The aircraft prototype testing, no matter how extensive, did not "cane" the equipment as much as the operator could in three weeks. He disagreed that civil equipment might not be applicable to military aircraft. It might not be from the point of view of operating conditions, but from the point of view of reliability the civil operators' experience was vital.

Whatever the period stated for the operation of equipment between overhauls, the important factor was that it must be capable of functioning correctly for at least that period. It was better to specify 100 hours, if they were convinced that it would not fail within that time, than to pretend that it would operate for 500 hours.

He wondered if on the operating voltage of actuators and other equipment there was too much outside the control of the aircraft designer. Particularly with 24-volt applications, the ground truck situation throughout the world was chaotic and, while that situation existed, to achieve serviceability they would have to accept some penalties so that equipment would operate at much lower voltages than seemed reasonable. If some sort of auxiliary generating plant were fitted and the aeroplane were self-contained, they might relieve that problem. He could not see how, particularly in wartime conditions, the elaborate ground servicing proposals now being made would be maintained.

He disagreed that development ended with production; he thought that it started at that stage. As the authors had said, they never had time to make a piece of equipment and then think about it and hand it to an aircraft constructor about a year later; they actually made it for a job which was going out, and the production stage was just the beginning of the real development of the equipment on the aeroplane.

What were the authors' opinions on oil seals, which had been a cause of trouble?

An illustration had been shown of a motor generator with a tin box on the top, as an example of how not to do things; it was a bad mistake, which he hoped would never be repeated, to put a flimsy tin box on top of a heavy machine, when the unit had to be carried around in an elaborate container so that it should not be damaged by somebody lifting it, stepping on it or dropping it on one corner. It would always be dropped immediately after it was taken out of stores.

G. W. Trevelyan (The de Havilland Aircraft Co. Ltd.): Until fairly recently generators and other gear seemed to have been developed without much attention being given to cooling, which had to be achieved as best it could be in the particular installations. Obviously it was a problem, particularly at

high altitude. It was only during the past few years that aircraft had been operating at 40,000 ft. and more, and it had become important that the electrical gear should be designed for cooling as well as for efficiency, compactness and lightness.

There were three main characteristics with a bearing on cooling, namely, the overall efficiency of the generator or other gear, the efficiency of the heat exchange and obviously, for air cooling the pressure drop laws for the apparatus.

For the first, it was most essential to attain the highest possible efficiency, for any reduction increased the cooling requirements severely. The same consideration applied to heat exchange characteristics; and from the point of view of reducing pressure drop, all restrictions in the system should be avoided as far as possible.

The authors had suggested that it might be possible to increase operating temperatures, but it was essential that any allowable increase of operating temperature should ease the cooling problem, rather than bring down the size of the machine and leave the cooling problem where it was.

It was also essential to test the cooling of generators, etc., on ground rigs for high altitude conditions as well as for low altitudes. It was easy enough to do the sea level tests, but it was essential to get the complete cooling characteristics before the apparatus was flight tested. His Company were glad to co-operate with the electrical manufacturers in such tests, but they felt that the makers themselves should have complete facilities for all the tests on cooling at high altitudes, high temperatures, and so forth.

The more the speeds of aircraft increased, the more severe the cooling problem became, and it was essential that the electrical apparatus should be designed in close co-operation with the aircraft designers in order to ease cooling and other problems.

E. Lloyd (Air Registration Board, *Associate Fellow*): He agreed generally with the proposed period of 1,000 hours between overhauls, but was more interested in the random defect rates occurring within that time. In the past they had been so high and so scattered as to render the "overhaul life" almost meaningless; and even with new equipment a failure rate of one per 10 time expired items was considered reasonably good. He would like to see that ratio more like 100/1, and he believed that that could be achieved by even greater attention to detail design, the elimination of the bits of solder, the broken connections, and so on. He agreed that things were better than before; but it was because of the random failure rate that in some cases the Air Registration Board had had to insist on the duplication of electrical devices in de-icing and fuel systems and vital engine and propeller controls. The improvement of reliability in the way he had suggested might well produce quite a useful overall saving in weight.

He agreed with the authors' remarks on bearings, and found Mr. Follett's remarks very encouraging, but he wondered what could be done by close inspection and selection of existing types of bearings until the new ones were ready; by that practice British European Airways had obtained encouraging results, increasing both the life and the reliability of bearings.

He appreciated the close attention that was given to protection equipment; on 108-volt systems arc failures to light alloys could be spectacular. Had tests been made to determine what degree of damage could be done within the rupturing time of the breakers?

He agreed that double faults might occur on military aircraft, but he still asked that consideration be given to all the single faults on civil aircraft, particularly on the higher voltage systems, because inevitably they occurred.

A. J. Cope (British European Airways, *Associate Fellow*): That evening he had checked the defects report on the ball bearing inspection which was being made by B.E.A.; he had not had time to make an accurate assessment, but the bearing failures accounted for less than 10 per cent. of the total failures, and probably more than 5 per cent. Of the last batch of bearings received it had been necessary to turn back more than 50 per cent. as being useless for electrical equipment. They could not really afford to waste their time inspecting new bearings; but if they could find that bearings were wrong, presumably the manufacturers could do so also.

Operators did not like opening up equipment in order to inspect it; they would rather leave it on the aircraft and not touch it. The period of 1,000 hours between overhauls for generators and magnetos was reasonable, in the present state of knowledge. Actuators, however, were running for less than 10 per

cent. of the flying time of the aircraft; in 1,000 hours of running of a generator an actuator ran for less than 100 hours, and he felt that something like 3,000 hours between overhauls was much nearer the mark for actuators. The trouble was probably vibration.

With regard to "off" and "on" actuators, designers were inclined to say that they had electrics pressed upon them. For operating things like fuel cocks, and trimmers, operators were not happy about electrics; it was no use having 500 gallons of fuel in a tank which could not be used because the valve actuator had gone wrong. He felt that electrics had not reached the standard of the rod for operating such things.

Where possible, B.E.A. helped manufacturers by testing pieces of new equipment on aircraft, bearing in mind at the same time that their chief object in life was to carry cash customers, and that they must comply with regulations.

A. K. Clyde (R.D.Inst., Ministry of Supply): He had some figures of defects on two well-known generators, now rather obsolete or obsolescent, Types KX and HX. Of those defects, 20 per cent. were due to bearings; the remainder were due to the shafts, the armature, broken connections, brushgear and terminals; the terminals accounted for 15 per cent. of the defects. Those figures pointed to the fact that bearings did not represent the only issue in defects. It was also significant that two-thirds of the bearing defects occurred in the non-driving end. He felt that the problem fell back on to the designers of the machines.

Work was being done on pneumatic bearings; they had the great advantage that there was nothing to cause wear, except air, which it was hoped was easy to get; and the power required for those bearings more or less balanced the improvement in efficiency due to the absence of friction.

It seemed that two factors which reduced reliability were high speeds and high temperatures. The authors had said that they were planning for higher speeds and temperatures, but he felt that they were going the wrong way.

One thing that could be done about high temperatures was to consider new methods of cooling. It had been mentioned in the discussion that, although there was plenty of air at altitude, they could not get enough through the machine. It would be worth while perhaps to investigate vapour cooling, by injecting water into the machine, relying on its latent heat of vaporisation and taking out the steam, condensing and using it again. An interesting thing about it was that, whereas for one lb. of air, for a temperature rise of 30°C., 12.9 B.Th.U. could be absorbed, for one lb. of water, vaporising at 34°C., 970 B.Th.U. could be absorbed. What were the authors' views on this matter? He thought there were many advantages in this system — more efficient heat transfer, no high altitude brush wear, simple installation (instead of running 2-in. pipes to carry the air they needed only about ½-in. pipe), and ground cooling was simplified; it was necessary only to switch on a small pump.

How had the authors arrived at the conclusion implied, that the reduction of the period between overhauls would result in reduced weight? He did not see what difference it would make to the weight.

C. C. Jackson (de Havilland Aircraft Co. Ltd.): The electrical industry had produced, often at short notice, equipment of higher performance and reliability than that to which the Aircraft Industry had formerly been accustomed, but in the written paper signs of complacency and misdirected effort could be detected. A number of failures of the old avoidable type were still experienced, and an examination was made of the defect reports on associated electrical apparatus in which more than 230 instances of equipment failure had been reported. Extracts from reports read: "It was discovered that the above mentioned modification had not been carried out" (by the makers); another, "The fault is considered to be due to a variation in the bimetal strip characteristic"; and another, "The bearing had seized due to the bearing being faulty." Many more of a similar nature could be mentioned.

The solderless connectors had not succeeded by any means in eliminating the human element, for there were still breakdowns caused by faulty tags or ferrules and to the nicking of cable conductor strands in the stripping process. Strict attention to shop processes and tools could reduce that considerably, but a few faults escaping detection could have serious consequences.

There had also been occasion to increase conductor size to more than twice that indicated by the rated current consumption of apparatus, as the limit switches had an

erratic performance at the lower rated voltage, causing the apparatus to demand stalling current, with its effect on line drop.

Was it wise to pursue the design and development of bigger D.C. generators, in view of the fact that the brush performance at heights of 45,000 ft. or more was, to say the least, poor? Were the manufacturers confident that that problem would be solved in the near future?

The rectified A.C. scheme had much to recommend it, and with the current type of alternator a brush wear of 0.1 in. only had been measured after 40-50 hours above 40,000 ft.

In making use of improved materials, both from the heat resistance and weight saving points of view, development must not proceed beyond usable limits; and if by chance that had been done in the past in order to save weight regardless of reliability, the aircraft manufacturer was prepared to face an increase in weight, or not so drastic a weight reduction, in order to establish a sensible balance between weight and reliability.

Continuous co-operation was needed between the Aircraft Industry and designers and engineers of the electrical industry to keep informed on new problems and conditions arising out of progress in aircraft design.

I. O. Hockmeyer (*Associate Fellow*) *contributed*: Designing for a life of 1,000 hours would be comparatively simple if it were known that the first part to fail would fail when a certain critical wear had been reached and if the rate of wear were uniform and measurable. Brush life might conceivably be of this sort. Presumably in practice the cost of failures was imponderable and the meaning of designing for a 1,000 hour life was more an exercise in statistics than controlled experimental design. It would be interesting to see a number of histograms relating numbers reaching multiples of 200 hour life against life lengths in 200 hour multiples for different items of equipment in the same class and for different classes of equipment. The scatter would show how random those lives were and give more meaning to any selected replacement life, such as the 1,000 hour objective.

Maintenance of constant voltage at the source, which was not stressed in the paper, was more important than the cable voltage drop and should be a major line of development. If a range of 18 to 28 volts were to be covered a penalty in weight had to be paid in generation, distribution and consuming equipment. It was partly due to the additional local voltage regulators which should be incorporated and which were themselves inherent sources of unserviceability.

A case for the use of expensive materials was well made, but did expense also imply rarity? The lesson of the 1939-45 War must be learned in relation to military aircraft that potential production bottle-necks should not be created in the design office by impracticable specifications. The modified design after concessions in manufacture had been obtained, might well be inferior to an initial design that was based on realities.

REPLY TO THE DISCUSSION

MR. HIGGS

Mr. Follett: In general they were in wholehearted agreement with Mr. Follett's remarks, but the title of the paper had been imposed upon them.

They had felt that with modern methods existing equipment could have its life increased to 500 hours and at the same time the power/weight ratio could be improved: they considered that if they were to lengthen the life to 1,000 hours they would probably have to increase the weight, and they wondered whether that was really worth while on a high-performance fighter, for example.

They were pleased and relieved to hear Mr. Follett's remarks about ball bearings, for they felt certain that better bearings could be made; they would try to apply them to their machines, and to improve methods of assembly and alinement.

Mr. Edwards: They also were worried about such mistakes as dropping blobs of solder here and there. But most of those rather stupid and irritating failures occurred when manufacturers were trying to rush equipment through the experimental department, when they had to stand over some poor fellow and urge him to finish the job because they wanted to whip it away quickly, and he probably forgot to wipe his iron, or something of that sort. So that it was partly the fault of the customers. That type of careless mistake, of course, pointed to faulty

inspection, but it must be realised that because of the specialised nature of most aircraft equipment, particularly in connection with reduced size, quite an important part of the development consisted of learning how to assemble components after the designers had reduced the size to a minimum. This related to the request made in the paper for as much time as possible to be allowed for the development of new equipment.

It seemed that Mr. Edwards had rather missed the point about A.C. systems. The system of transferring loads from one alternator to another occurred only when running separate generators, not in parallel. At one time he was rather keen on the idea of separate feeders, fed from individual alternators with the associated automatic load transfer and the rest; but a hook-up was tried on the bench and he had quickly changed his ideas because of the complications which became necessary. The view now was that, if A.C. were to be used, and A.C. power, the alternators must be run in parallel, which meant providing a constant-speed drive. In fact, 400 c.p.s. alternators had a high synchronising torque, and when they were in parallel they would remain in parallel fairly easily. But it was necessary to have the constant-speed drive. He felt the only answer would be to have a small auxiliary set, which for modern aircraft obviously had to be a small gas turbine. He had looked into that problem and found that a small gas turbine complete with alternator could be made giving a power/weight ratio of about $1\frac{1}{2}$ lb. per kw.; but unfortunately it had consumed its own weight in fuel about every twenty minutes. There were perhaps other ways of doing the job, and this was one of the developments for the future that must not be overlooked.

He and Mr. Woodall thanked Mr. Edwards for the kind remarks he had made towards the end of his contribution, to make up for the rather "rough stuff" at the beginning! Much of the criticism levelled at electrics was justified in part and such criticism, if constructive, was welcomed by the authors.

MR. WOODALL

Mr. Woodford: He thought Mr. Woodford was a little pessimistic about the 112-volt system. There were difficulties, they knew; there were problems of protection on 112-volt systems. But reverse current circuit breakers were already designed and tested to break at 8,000 amps., 112 volts, at 40,000 ft.; so that at least they had moved some way towards solving the problem.

Mr. Woodford had talked of the merits of the A.C. system and they gathered that he was extolling the virtues of a varying frequency system, or the frequency wild system, as it was referred to in the United States. But the authors were not really in favour of a system in which the frequency could vary 5/1, or even $3\frac{1}{2}/1$. Many of the services on aircraft demanded a constant frequency. If they were to have A.C., let them make full use of it at constant frequency and thereby eliminate the numerous converters with which —and he believed Mr. Edwards would agree—aircraft were now cluttered.

Mr. Cronbach: At the production stage there was still much to be done; and, as Mr. Follett had pointed out, it was of no use subjecting one or two machines to long tests, there should be many such tests. There was always a shortage of prototypes; the small number available when the real endurance test work should start was a great drawback. So that inevitably they had to wait for the production stage before any large-scale testing could be done and by that time the components would probably be in service.

The oil seal was always a source of contention. The normal synthetic rubber seals were not really up to their job; better synthetics were required to meet the high temperature conditions now experienced, for the normal synthetic rubber seals would not withstand much more than 130°-140°C. Another factor was that the finish of shafts should be considerably improved. Some of the trouble with seals had been due to an inadequate appreciation of the finish required. Nevertheless, there was room for better seals.

MR. HIGGS

Mr. Cronbach: The flimsy box was made originally in a thin gauge aluminium and was as light in weight as was possible, consistent with reasonable handling. For transport purposes a special case had been designed and made and it was rather disappointing to learn that the first thing that happened to the equipment when removed from its packing case was that it was "dropped on one corner." As a result of the experience on this particular equipment it had been necessary to stiffen the box, with an increase of

approximately one lb. in weight, on this and several other similar machines.

The whole question of covers was one of great controversy. On a range of motors the end covers were originally made in thin gauge aluminium. Those covers were so flimsy that fairly careful handling was necessary; eventually it was considered desirable to use steel covers in the same gauge, since thicker aluminium covers of the same strength were heavier. After some time those motors came under the scrutiny of a weight-saving panel and they were much criticised for using steel instead of aluminium. Today, covers were available both in steel and light alloys, but steel was always used where a dented cover could cause serious trouble, such as over a fan.

Mr. Trevelyan: The design of light-weight aircraft equipment was often referred to as being a problem comparable with that of getting a quart into a pint pot. But they only thought they got a quart into a pint pot. The manufacturers had decreased the size of generators considerably over the years at the expense of efficiency by cramping and condensing things, so that it had become almost impossible to get any cooling air into them. A stage was reached at which the type P generator had a pressure drop of about 10 in. water gauge; that was subsequently reduced to 8 in., and the latest specification for new generators stated that it must not exceed 6 in. His Company had collaborated with the de Havilland Co. and Mr. Trevelyan in connection with a generator in which they had thought they had done a good job in reducing the pressure drop to 6 in. This had been further reduced as the result of suggestions that the de Havilland Company had made, and even so the cooling of this particular generator presented difficulties in the aircraft.

The problem of cooling was serious and had to be considered in connection with many designs. Quite recently it was discovered that the normal aircraft continuously running a D.C. motor, fan-cooled, would not run light at a height of 50,000 ft. simply because the normal fan could not provide enough air through the motor to get rid of the light running losses. That had caused concern to people who were trying to cool motors in the unpressurised portions of aircraft, since they were forced to provide blast cooling which quite often affected an aircraft's performance, quite apart from the added complication and difficulty of providing pipes, etc. Much more had to be done to reduce the pressure drop, but he did not see how it could be done except by providing easier passages through the machines; and that, in general, would mean larger and heavier machines.

That was the price which would have to be paid if the available pressure drop could not be maintained at, or increased above, 6 in. The electrical manufacturers would like about 15 in.; but if they were limited to 3 or 4 in., as had been suggested, the Aircraft Industry would have to pay for it by way of increased weight.

MR. WOODALL

Mr. Lloyd: He felt that Mr. Lloyd was right, that the odd cases of failure really mattered and that they would like to see figures not worse than one in 100 defects in the 1,000-hour period.

On ball bearings, Mr. Follett had given some gleam of hope. But the action which Mr. Follett had in mind might not ensure supplies of bearings of better design and workmanship from all the manufacturers; the fact that one small firm would make the precision bearings would not be of much help to the industry. His Company had to show three or four different types of bearings on all their drawings because the supply position was so difficult. Nevertheless, it was encouraging to know that the Ministry of Supply were sponsoring the work.

All bearings were delivered on release notes, which suggested that they had been fully inspected by the manufacturers and re-inspected by the A.I.D. In spite of this procedure and the high price paid for the bearings, too many faults were found by his Company on check inspection. He would like to hear from some of the bearing manufecturers on that matter, which was important.

MR. HIGGS

Mr. Lloyd: On the question of rupturing time of circuit breakers, he confirmed the necessity for high-speed units referred to in the paper. A fault current normally rose to a peak rapidly and then died away exponentially. It was common practice in industrial work to let the system and the circuit breaker ride through the peak and to open the breaker on the dying current. From tests taken on aircraft equipment it was most

important that the fault current be interrupted if possible before the peak was reached. That was particularly important if the fault current were to an airframe member or to the skin.

Mr. Cope: He thought that Mr. Cope had gone astray a little on the actuator question. Surely the problem with the actuator was tied up with the number of times it operated; if it would operate without attention for 1,000 hours of flying, that was good. He did not see why it should be singled out for a life of 3,000 hours' flying. Probably it was difficult to determine how many times it would operate during 1,000 hours of flying, but surely that was the criterion.

One of the biggest causes of trouble with electrics was over-enthusiasm of application. If a rod or cable control could be used economically then it should be obvious that that was the correct thing to do, rather than to use some other "clever" and more complicated method. There were many cases where a mechanical system would be difficult and perhaps even impossible to apply; that was the stage at which to bring in electrics.

MR. WOODALL

Mr. Cope: Small electrical actuators were first introduced for engine controls and replaced pneumatic jacks which were not giving satisfaction. As stated in the paper, teething troubles were apparent, due perhaps to "over - miniaturisation." Small D.C. motors required considerable development before reasonable reliability could be established. The small A.C. actuator employing a squirrel cage motor could become an extremely reliable piece of apparatus and it might ultimately become a proposition for a small A.C. supply to be provided to feed a number of actuators of that type.

His firm had been very grateful to B.E.A. for their help in testing improved ignition and starting equipment from time to time. This had proved to be a quicker way of proving desirable modifications, than by tests at engine manufacturers.

Mr. Clyde: He did not think that either Mr. Higgs or he had actually said that bearings were the only cause of trouble in electrical machines. What they had said was that lubrication was really vital, and that bearings had failed more often than not through lack of lubricants. Therefore, they felt that bearings should be sealed, and it was the reluctance on the part of British bearing manufacturers to supply sealed bearings, or bearings which were special in any way, that had led to their remarks. If bearings were sealed and contained the best possible grease, the majority of them would run for a long time. Nevertheless, his Company had rejected large numbers of bearings when they were received, although they had only made a railway journey since leaving the contractors' works.

The work on pneumatic bearings was a worth while line of development. The authors had looked into the matter, but were not in a position to say much about it at present.

He did not altogether agree with Mr. Clyde's suggestion that they wanted lower speeds and lower temperatures. After all, the aeroplane had to fly and, therefore, the weight question was vital.

He had gained an impression from some of the comments that weight was of minor importance, but this certainly varied from his Company's normal experience. The Ministry sent letters urging a reduction in weight and the constructors forced the accessory manufacturers to make extensive modifications to designs to save only a few ounces in weight. Were industrial machines used, working at relatively low speeds and temperatures, then undoubtedly a high standard of reliability and overhaul life would be achieved. Unfortunately, this was not a practicable solution for aircraft equipment.

In the authors' experience, quite small increases in weight had often resulted in a marked increase in reliability. It was necessary to exercise a balanced judgment, but in this, as in so many other aspects of aircraft design, a policy of intelligent compromise was often the right course to take.

Mr. Clyde's suggestion for vapour cooling of generators was interesting, but the authors felt that they were not in a position to comment on that proposal at this stage.

MR. HIGGS

Mr. Clyde: From Fig. 2 in the paper it would be seen how weight had been reduced in aircraft motors—the time between overhauls on the motors shown in that figure was nearly directly proportional to the size and weight. The normal 4 pole, 1,500 r.p.m. induction motor in many instances ran con-

tinuously for several years without any attention at all.

Mr. Jackson: They felt that Mr. Jackson in the main had elaborated on a few of the difficulties referred to in the paper. Regarding solderless connections it was felt that the biggest difficulty with electrical connections was to evolve some means whereby joints could be adequately inspected so as to detect faulty joints without either breaking or weakening the good ones. All too often electrical connections were inspected by a process of flexing the wire until it broke. Short of insisting that every connection be examined as it was made it was extremely difficult to ensure an adequate inspection procedure. That was one of the cases where, as suggested by Mr. Jackson, a careful study of the factory methods must be made and a rigid application of the correct method be applied at all times.

They had tried to avoid a controversy on the use of A.C. generators and rectifiers instead of D.C. generators. They would repeat their earlier statements that the simple A.C. machine was always to be preferred to the more complicated D.C. machine if it were practical; there were many cases however when a D.C. installation was more simple and desirable.

Mr. Hockmeyer: In designing for a life of 1,000 hours, the object was to produce an item which could perform its normal function for 1,000 hours without any attention whatsoever. Unfortunately, it was usually impossible to make a test to prove the 1,000 hours life as defined, under the actual operating conditions experienced in the aircraft. Generally speaking, if under normal bench conditions a unit could be run at its full load continuously without attention for 1,000 hours, there was not much likelihood of a failure during 1,000 hours in aircraft conditions. Any failures that did occur in less than 1,000 hours would probably be due to faulty manufacture and carelessness of the type referred to by Mr. Edwards.

It was agreed that the maintenance of a constant voltage at the source was most important and conditions now were far better than those which prevailed during the 1939-45 War. The equipment manufacturer was only interested in the voltage he received at the terminals of his apparatus and, speaking in general terms, the smaller the range of voltage to be covered at the terminals, the lighter would be the equipment. The point which they wished to make in the paper was that the electrical industry was being criticised for failure of apparatus to operate at a terminal voltage as low as 18 when the initial design of the apparatus was only intended to cover a range of 25-28 volts. If for weight considerations it was economical to use a cable giving a very high voltage drop, the designer of the equipment connected to the end of this cable must be consulted to see whether his apparatus would operate at the resulting low voltage.

PROGRESS TOWARDS HYDRAULIC SERVICEABILITY

by

R. H. BOUND, F.R.Ae.S. and H. G. CONWAY, F.R.Ae.S.

THE 822nd Lecture to be read before the Royal Aeronautical Society, "Progress Towards Hydraulic Serviceability," was given by R. H. Bound, F.R.Ae.S., and H. G. Conway, F.R.Ae.S., on 15th March 1951 at the Institution of Civil Engineers, Great George Street, S.W.1. Major G. P. Bulman, C.B.E., F.R.Ae.S., President of the Society, presided at the meeting and introduced the lecturers, Mr. R. H. Bound, Technical Director of Dowty Equipment Ltd., and Mr. H. G. Conway, Technical Director of British Messier Ltd.

INTRODUCTION

To be asked to prepare a paper for delivery to the Royal Aeronautical Society on the subject of the serviceability of a product with whose design the authors are closely associated, offers an excellent opportunity for a critical survey of the field, uninfluenced by commercial considerations and with the realisation that the admission of faults, where present, is essential for constructive consideration of the whole problem.

The hydraulic installation of an aircraft is now such an important and integral item of equipment that any steps which may be taken towards improved performance in serviceability would contribute notably to the operational success of transport and military aircraft. The degree of complexity required in modern aircraft hydraulic systems is such as to make impossible a completely fool-proof system. But consideration of factors which keep trouble within very small bounds is of vital importance.

This paper is not concerned with considerations of the competitive performance of either equivalent pneumatic or electric devices. This aspect has been discussed on many occasions before this and other Institutions—three papers on the subject which were given at the 1949 Anglo-American Conference can be referred to particularly. The point was made during that Conference that 99 per cent. of the world's aircraft are fitted with hydraulic equipment. This in itself answers those who would suggest overcoming the difficulties experienced with hydraulic systems by their complete elimination.

THE EXTENT OF THE MODERN HYDRAULIC SYSTEM

The first hydraulic systems were fitted to aircraft in the period 1934-1935 and were confined to undercarriage retraction and flap operation. Automatic devices were not used and the pump was unloaded manually. Such refinements as thermal relief valves, hydraulic locks, flow synchronisers, and so on, were unknown.

By 1939, the extent of hydraulic systems had increased by the addition of bomb door operation and occasionally other services.

As the comparison in Table I shows, the trend with the typical bomber of today is towards a great increase in the number of services operated hydraulically and to a much higher degree of emergency protection, involving system duplication. Table I compares the hydraulic services on a Lancaster bomber with those of a typical bomber of the present generation.

Table I shows that the number of services in the modern bomber has introduced a considerable degree of additional complication. The fixed tail wheel has been replaced by the retractable and steerable nose wheel. The mechanical inter-connection of undercarriage doors to the landing gear is often not possible now, and separate hydraulic

jacks with sequence control are required to operate the doors.

Pneumatic brakes are often replaced with hydraulically operated disc brakes, in some cases the latter being fitted with automatic skid detection devices which involve additional piping and controls. Dive and dive recovery flaps are a new requirement. Many additional services must be operated under conditions of emergency (as when a pipe is broken, or damaged by gun fire), and this has meant that the bomb door circuit must be operated in both directions by emergency means. Power flying controls operated either from the main or an auxiliary system will be fitted on many aircraft, thus adding to the complication.

The comparisons already made are best appreciated by inspection of Figs. 1 and 2, the former showing the Lancaster system, and the latter a present-day bomber system. (In this case power flying controls are not shown).

The modern systems demand skilful design if reliability is to be achieved.

EMERGENCY SYSTEMS

On several occasions in recent lectures reference has been made to over-complication caused through the provision of emergency devices. These introduce additional complications which may lower the overall reliability of the system. Some aircraft are not provided with any emergency undercarriage lowering system other than gravity. Most aircraft, however, are fitted with an emergency system which will lower the undercarriage, in some cases involving work to put the system back in good order.

It is also easy to fall into the habit of providing indicator lights to act as warning devices to eliminate the complication of automatic emergency protection. This can be carried to extremes; on one occasion it was pointed out that if all the warning lights were illuminated at the same time, no less than fifty-six lamps would be lighted.

It is often better to provide an adequate degree of safety or reliability in the original system, than to introduce a secondary system to deal with a possible failure.

TYPES OF UNSERVICEABILITY ENCOUNTERED

It will be appropriate to review briefly the types of unserviceability which have been experienced, drawing upon the knowledge of the firms with which the authors are associated, and on information obtained during discussions with maintenance commands, the airline operators and service managers at aircraft firms. Later on, the means of eliminating some of these difficulties will be considered in detail.

TABLE I

COMPARISON OF HYDRAULICALLY-OPERATED SERVICES

Lancaster		*Modern Bomber*	
The following services are operated hydraulically:		The following services are operated hydraulically:	
Main undercarriage Wing flaps Bomb doors Hot air intake Fuel jettison		Main undercarriage Main undercarriage doors Nose wheel undercarriage Wing flaps Bomb doors Dive brakes Dive recovery brakes Camera door Wheel brakes Nosewheel steering (Power flying controls to all services)	
	No.		*No.*
Hydraulic pumps ...	2	Hydraulic pumps...	5*
Hydraulic jacks ...	17	Hydraulic jacks ...	25*
Selector valves ...	7	Selector valves ...	14*
Total of hydraulic components (other than pipe connections)	51	Total of hydraulic components (other than pipe connections)	135*
	ft.		*ft.*
Approximate total length of piping ...	230	Approximate total length of piping	1,450

*Excluding flying control systems

Troubles can usually be divided into two types:

(*a*) those which are experienced with a new type of aircraft;

(*b*) those which occur even on well established aircraft.

The first type of trouble arises because sometimes there is insufficient time for the hydraulic engineer fully to develop his equipment. Hydraulic systems on each prototype aircraft differ in such matters as pipe runs, pipe bends, reservoir position and so on. These are factors which necessitate the testing of every new system to ensure satisfactory operation. Notwithstanding that all the components have been fully tested, the system can prove at fault through variations in the installation.

Another difficulty is the inability of the hydraulics engineer to test the complete system under altitude conditions and this, in certain circumstances, can give rise to troubles.

It is general practice nowadays to build extensive rigs on which the systems are tested, but sometimes the hydraulic engineer has insufficient time to complete tests on the rig before the aircraft flies. No rig, however perfect, can simulate exactly flight conditions.

Examples of difficulties on new types of aircraft are:

(*a*) On one aircraft the reliability of a particular type of hydraulic pump is so bad that it has had to be changed to one of another make, although the pump in question is of proved design and has been used successfully on many types of aircraft. The faults in question are undoubtedly connected with the particular installation.

(*b*) Difficulty with another system due to inadequate cooling causing an excessive temperature rise.

The authors have been in some difficulty in obtaining accurate statistical information on the second type of trouble, that which cannot be attributed directly to the lack of development. Isolated items of information are readily available and many maintenance engineers have crystallised their own viewpoint. A statistical appreciation of the problem is needed to enable the difficulties to be put in proper perspective. As an example of this can be cited the objection many engineers have to the use of hydraulic flexible pipes, which are claimed to be unreliable. Bearing in mind that a modern aircraft may have between thirty and fifty of these flexible pipes, it would be difficult to believe that a few failures were serious because the overall percentage, in terms of the numbers of pipes being used, would be extremely small.

The principal causes of troubles are known to include the following:

(*a*) fracturing of hydraulic pipes, usually at the pipe joint flare;

(*b*) leaking pipe connections;

(*c*) failure of seals;

(*d*) failure of a component due to swarf or dirt;

(*e*) failure due to faulty assembly;

(*f*) failure of hydraulic pump (for any of a number of possible causes, the chief of which are dirt and suction strangulation);

(*g*) secondary difficulties such as leakage due to corrosion;

(*h*) failures of flexible pipes.

LINES OF IMPROVEMENT

So far the likely types of failure which may be encountered have been reviewed. It is now up to the hydraulic engineer to put forward constructive suggestions. The various avenues of improvement are as follows:—

1. basic improvement in design;
2. improvement in testing technique to enable troubles to be eliminated at an early date;
3. improved installations to facilitate the assembly and removal of components.

These courses of action will now be considered in detail.

DESIGN

It may be assumed here that the complexity of the system has been reduced to a minimum. The first factor to be considered is that of pressure; although it has not been stated specifically, it is a fact that pressures have risen and will continue to rise as aircraft hydraulic power requirements increase. Higher operating pressures have enabled the weight of modern aircraft systems to be kept within reasonable bounds. It is of interest that the hydraulic power available on the Lancaster and Halifax bombers was about 12 h.p., compared with 30 h.p. on a modern bomber.

There is no direct evidence that hydraulic serviceability or reliability is affected by pressure. Hydraulic seals appear to be rather less reliable at high pressures than at low pressures, but evidence is not conclusive and other factors are often more critical. It is thought that increased pressures must be accepted. This must be qualified by saying that there is not much advantage to be gained in raising pressures of a system which is in continuous operation, as for example on powered flying controls operating at 3,000 p.s.i. There is, however, everything to be gained on large aircraft in raising the pressures on the remainder of the system to 4,000 p.s.i., or even higher.

A factor of considerable importance to the design of the system is the choice of

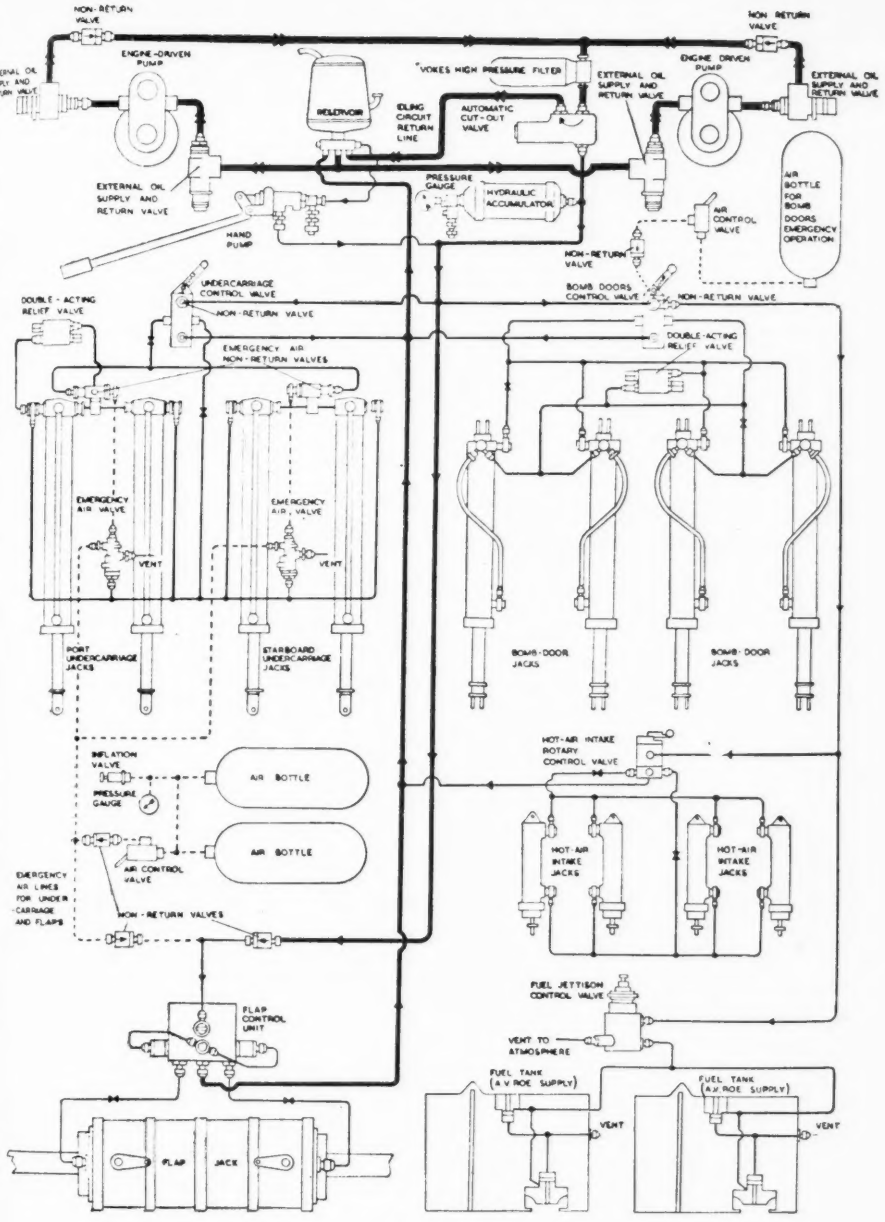

Fig. 1.
Hydraulic system of the Lancaster.

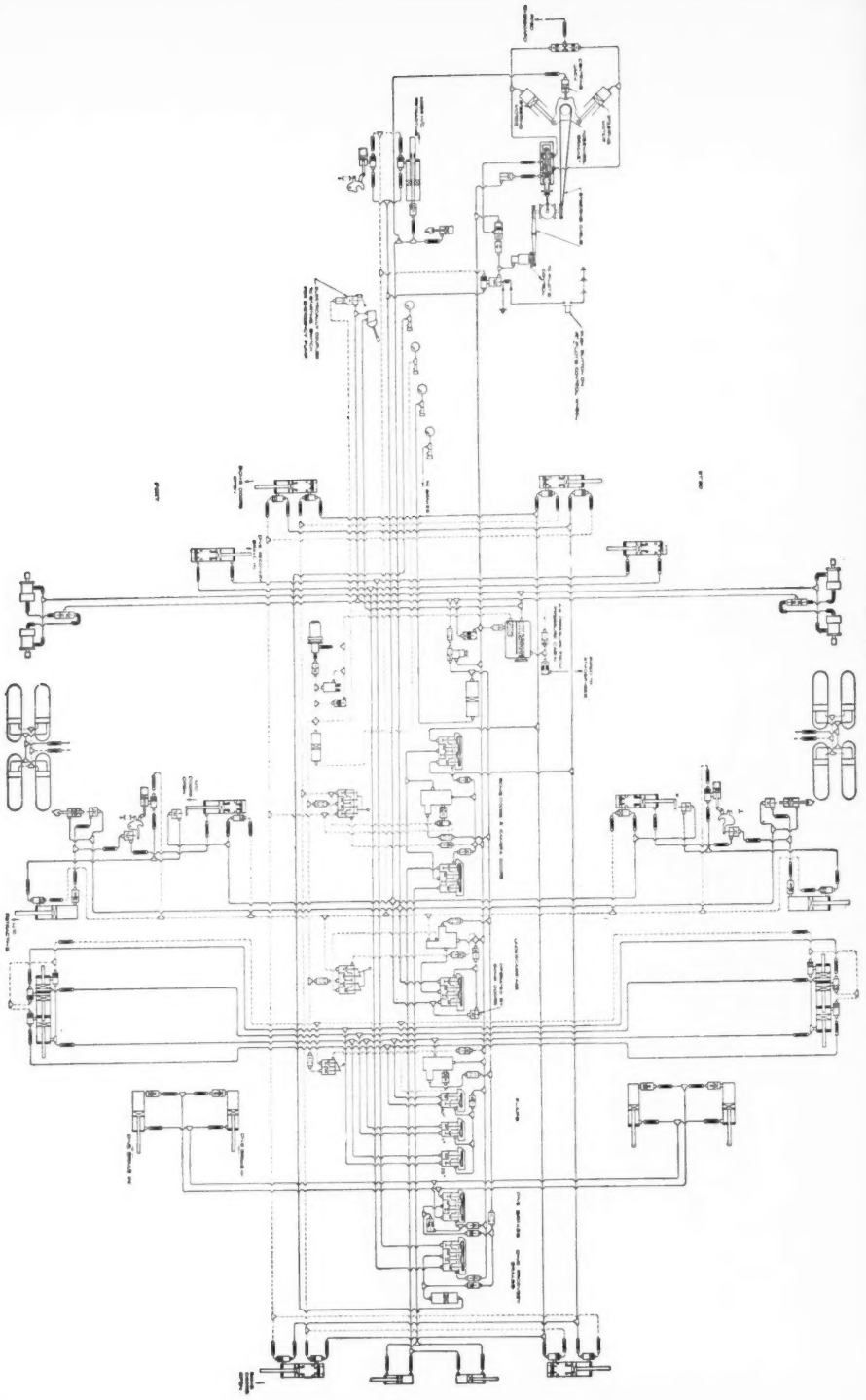

Fig. 2.

pump—whether of variable volume or constant type with cut-out—and resulting from this, whether the system shall be maintained under pressure or whether it shall be "off loaded." Some believe in the variable volume pump as a means of effecting an overall simplification of the system, and others believe that the performance of variable volume pumps leaves much to be desired and prefer the rather more complex system using an accumulator and cut-out as being more reliable, particularly when more than one pump is used. The authors believe that both types of pump have correct spheres of application. With both types of pump, however, it is normal practice to maintain the system under pressure and automatically to bring the pump into operation as soon as the system is selected and oil delivery is required.

The earliest hydraulic systems used a manual by-pass which was normally opened when the aircraft was in flight and the undercarriage and so on was retracted, and when hydraulic selection was required, the by-pass cock had first to be closed. A variation of this system was the so-called "open centre" circuit where the by-pass valve is contained within the main selector, the lever of which returned to a neutral position after completion of a selected operation. Due to the possibility of failure to close the by-pass valve and for the selected operation not to take place, this system fell into disrepute. Automatic systems were introduced about 1938.

There has now been a partial return to the earlier system on certain civil aircraft by the introduction of an off-loading valve with automatic cut-out so that the pump and system are not damaged if the pilot forgets to open the valve after take-off. On transport aircraft it is preferable to off-load the system to zero pressure, rather than to leave the pump cutting in and out to maintain the system at full pressure. Properly supported pipes should not fail if they are not under pressure. The off-loading system, therefore, appears to be of considerable benefit.

Whether such an off-loading system could be considered for a military aircraft is an interesting point. The authors believe that it might be considered for bomber and transport types of aircraft, but that it would not be practicable for fitment to a fighter or other short range aircraft. It is obviously not applicable to the part of the hydraulic system which may operate powered flying controls.

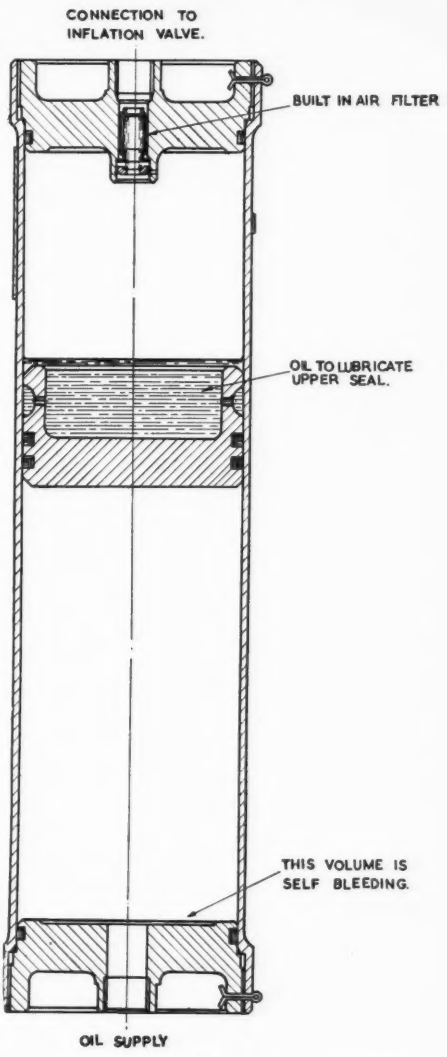

Fig. 3.
Lubrication of dry seals on an accumulator.

Another important point in design is to provide for easy maintenance at low temperatures. A simple operation may take five minutes at normal temperature, but 15 or 20 minutes at $-30°C$. Intricate operations such as fitting locking wire may be

Fig. 2. [illegible]

almost impossible to perform with cold, gloved hands.

Hydraulic Pumps

Reference has been made to the relative merits of variable volume and constant displacement pumps. A hydraulic pump is an item which requires much development before it can be considered satisfactory. The type test requirements for pumps are severe. While not suggesting that the present 100 hour type test schedule should be altered, pump designers should aim at a minimum life of 1,000 hours for a good hydraulic pump.

A type of pump which can be considered of variable volume is one which achieves this feature by the incorporation as a unit of a constant volume pump and a cut-out. This type of pump has advantages over the variable volume pump, but when two or four pumps are used in parallel, the normal type of pump with a single cut-out may be preferred.

Hydraulic Accumulators

The cylindrical piston type of accumulator has long been used in Great Britain and is now coming into service in the U.S.A. The "bag" or diaphragm type has been superseded on account of difficulties with the rubber diaphragm at low temperatures. The mounting of accumulators in a vertical position with the air chamber on top is recommended. The reliability of the piston glands can be improved if a small amount of oil is added to the top of the accumulator (air chamber), this acting as a lubricant to the air seal (Fig. 3). The practice of chromium plating the cylinder bores is one which is believed to be desirable.

Hydraulic Jacks

The practice of fitting jacks with internal locks is now well established, and the locking devices (of the collet type) are most reliable. The fitting of satisfactory indicators to these locks is difficult, particularly as the seals

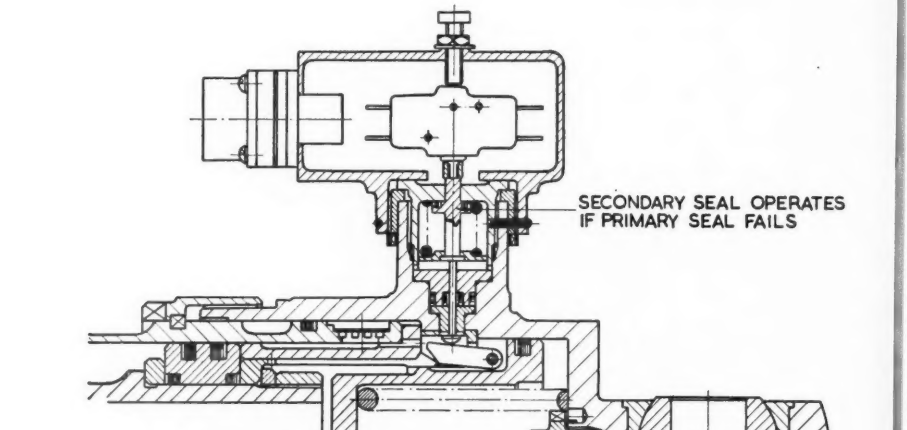
SECONDARY SEAL OPERATES IF PRIMARY SEAL FAILS
SPHERICAL EYE END
ONE WAY BREATHER TO PREVENT ENTRY OF MOISTURE
BUILT IN FILTRATION

Fig. 4.
Features of hydraulic jack construction.

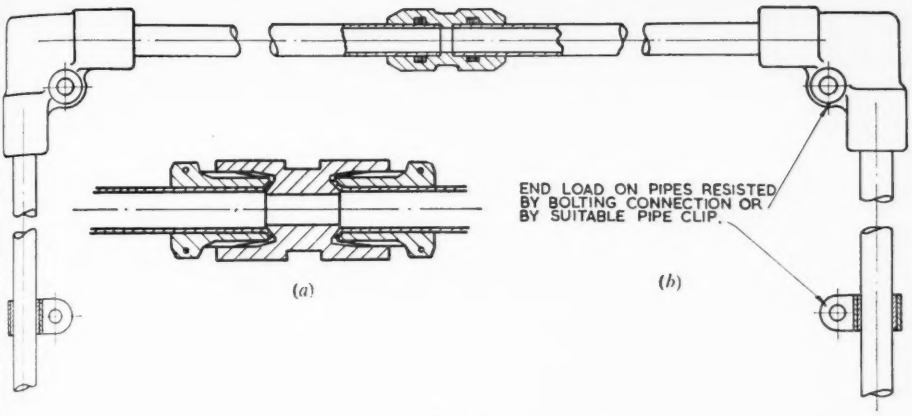

Fig. 5.

Improved pipe joints: (*a*) Internal cone type (*b*) Flare-less.

involved are of small dimensions. Fig. 4 illustrates how an additional seal will prevent loss of oil from the system if the primary seal fails. Hydraulic jacks can be improved by (*a*) the addition of built-in filtration, and (*b*) by hard chromium plating the cylinders and piston rods. The illustration shows one type of built-in filter.

Micro switches should be arranged so that wiring requires little or no movement when a jack is removed. A robust adjustment for switch position is essential.

Selectors and Valve Devices

Selectors and other types of valve normally rely on ball or poppet valves, or the cylindrical slide type of element. The earlier practice of using unguided balls has now been largely abandoned, as this led to indentation on the ball which permitted leakage. Modern practice is to use properly guided poppet valves, or a hardened steel ball trapped in a guiding member.

Plastic valve elements have been used successfully. The design and manufacture of cylindrical slide valves for use at the pressures common today is not easy. The clearances involved (0.0001 – 0.0002 in.), create problems of metal stabilisation and distortion under pressure. Partial locking and increase of friction occur with time, and are aggravated by "micronic" particles of swarf or dirt.

To ensure adequate valve life, endurance testing up to 100,000 cycles is now regarded as essential.

Piping

The general material now in use is steel or proprietary materials such as Tungum, and these may be considered reliable. The suitability of the material to stand flaring is a critical factor affecting reliability. Improved flaring technique to avoid sharp edges greatly increases reliability.

The weight of piping on modern aircraft represents as much as 30 per cent. of the total hydraulic system weight and research into the possibility of using pipes of reduced wall thickness in higher quality materials is important. High tensile steel tubing, bench formed and welded at "T" or Cross connections might be used.

The method of supporting the pipes affects the overall reliability of the system.

TABLE II

PIPE SUPPORTING RECOMMENDATIONS

Nominal pipe diameter, inches	*Maximum distance between supports, inches*
$\frac{1}{8}$	12
$\frac{3}{16}$	12
$\frac{1}{4}$	15
$\frac{5}{16}$	18
$\frac{3}{8}$	18
$\frac{7}{16}$	24
$\frac{1}{2}$	24
$\frac{9}{16}$	24
$\frac{5}{8}$	24
$\frac{3}{4}$	30
$\frac{7}{8}$	30
1	30

Table II illustrates what is considered to be suitable spacing of pipe clips. Pipe clips using a layer of vibration insulating rubber between the clip and the pipe are recommended. Installation of piping such that distortion of the aircraft does not cause undue stress in the pipes is important.

Pipe connections

The flared connection is now used in Britain and the U.S.A. and is considered satisfactory. Various different designs, not involving flaring, are used to some extent. In France, compression olive type connections are still used. The British A.G.S. connection is heavy, costly and is somewhat difficult to flare. The adoption in this country of the new Unified thread system creates an opportunity for a new type of connection. That illustrated in Fig. 5 (*a*) is suggested. The improved pipe support will be noted. Fig. 5 (*b*) shows a flare-less connection using rubber sealing rings. The unbalanced pressure force on the metal section of the pipe presents no difficulty.

It would be of interest to British engineers to know if the American use of tapered pipe threads, which replace copper or equivalent washers on adaptors, is a practice to be recommended.

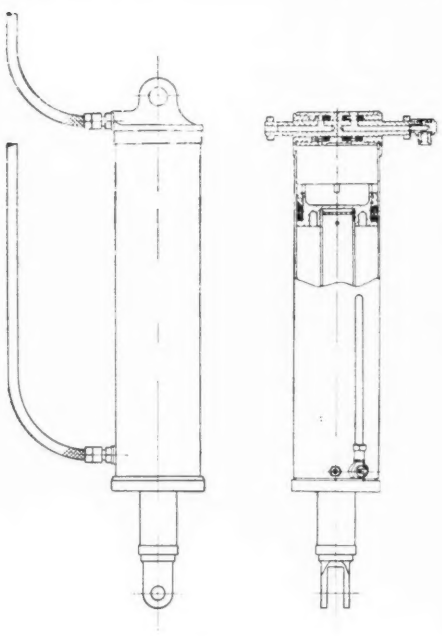

Fig. 6.
Flexible hose or rotary joint.

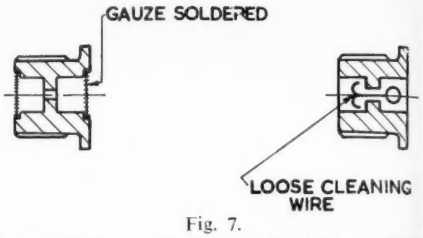

Fig. 7.
Means for preventing the choking of small orifices.

Flexible Hose

Flexible hose falls into two types, the normal low pressure cotton braided type and the high pressure steel cored variety. The defects in the former are almost always due to chafing or excessive movement of the hose. The cure is to support the pipe adequately.

With high pressure hose using a rigid core, it is essential that the end fittings be installed in, and remain in, the same plane during flexing. Considering the large number of hose on the average aircraft, the reliability is very good. An alternative to flexible piping is the use of swivel joints, either built into the jacks, or in the form of separate couplings. The authors differ in their views on the relative merits of the two systems.

Filtration

Good modern practice may be stated as follows:

(*a*) gauze protecting filters in the reservoir or in the pump suction line connection and also (with provision to prevent its removal) on the filler cap; (a practice which may be preferred in the future is to use "pressure-filling" by pumping oil into the reservoir from a hand-pump, thus dispensing with the normal filler cap and access panel);

(*b*) a very fine filter in the inlet connection to the automatic cut-out or the connection between the pump and the selectors. This filter should be of the so-called micronic type and capable of removing the smallest particle of foreign matter;

(*c*) gauze protective filters in the pipe lines at any point (such as ground test connections etc.), where there is a remote

chance of foreign matter being introduced into the system. Similar pipe line filters may be installed at the end of very long pipe runs;

(*d*) built-in filtration in components such as jacks.

The gauze protective filter in the tank is adequate to protect all but the most sensitive hydraulic pump and the use of this type of filter should not interfere with the suction characteristics of the pump. The micronic filter is introduced to protect the system from minute particles of metal due to abrasion of working parts, or contaminations in the hydraulic fluid. The gauze filters are used primarily to prevent swarf in the pipes from reaching the seals on the components.

Components having small orifices, such as restriction valves etc. should be fitted with built-in filters or, alternatively, be provided with automatic cleaning devices of some simple type. Fig. 7 shows a typical example.

Fluid

It is not likely that much development will take place in hydraulic fluid in the years to come, except in the introduction of some non-inflammable fluid or one with improved low temperature performance. Cases have occurred of water finding its way into oil drums containing the fluid and difficulties of corrosion in service have been experienced. It may be necessary for the adequate reliability of powered flying control systems to use specially filtered oil to eliminate difficulties with very fine particles of metal.

The re-introduction of castor-base fluids should not be encouraged on account of their inconvenience during servicing and maintenance.

Bleeding

Practice in regard to bleeding varies with different systems. It is good practice in the design of all components to eliminate air pockets, thus making the components self-bleeding. Where bleeding is essential, bleeder screws should be located at strategic points on jacks and so on, and with due regard to what happens to the oil being bled.

DEVELOPMENT TECHNIQUE

Modern practice in the development of an individual hydraulic component is to

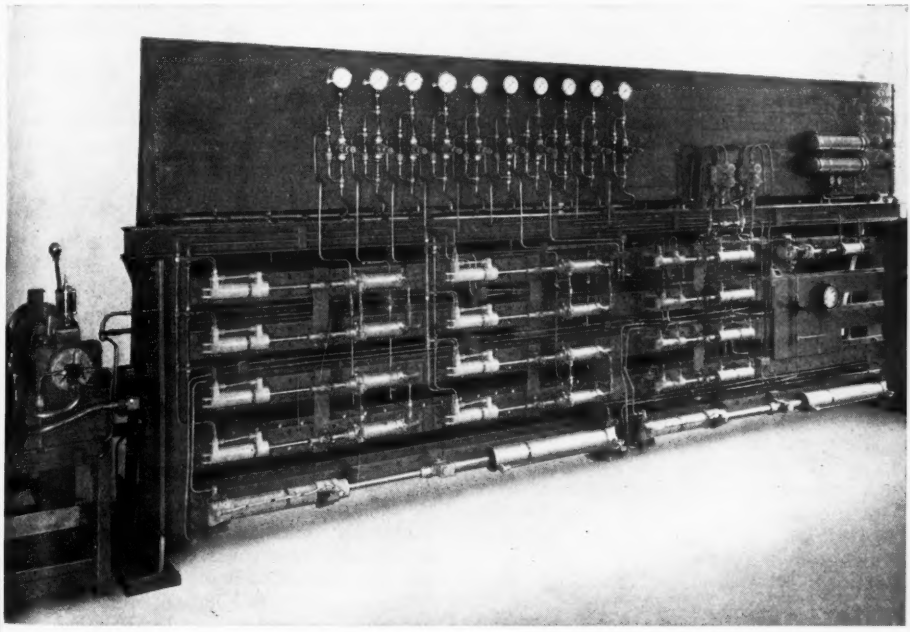

Fig. 8.
Typical hydraulic test rig.

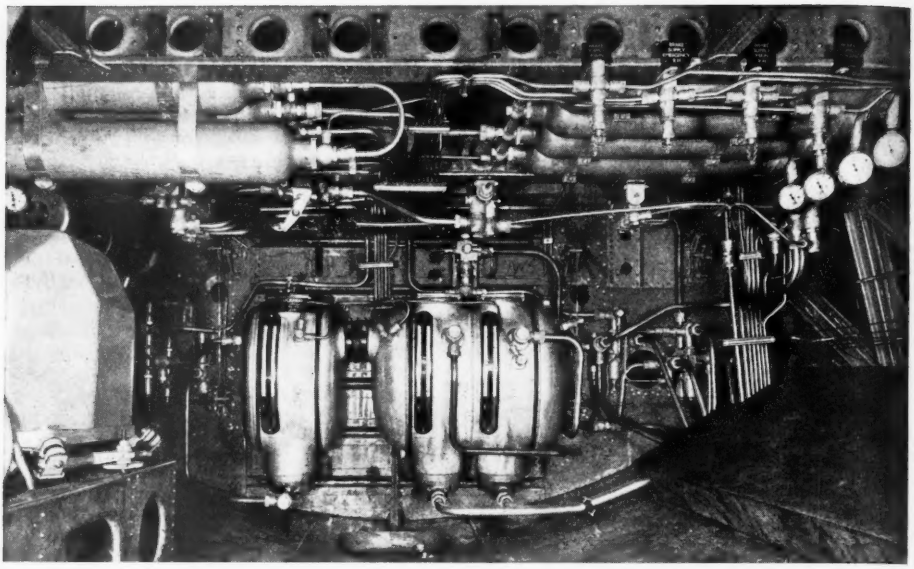

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Fig. 9.

Examples of good hydraulic component installation.

make many tests of the unit performance, culminating in an official series of tests in order to obtain the necessary official flight approval and so-called design clearance. Tests on a typical hydraulic selector, for example, would include the following:

(*a*) Pressure testing;

(*b*) Leakage testing;

(*c*) Endurance testing — operating, say, 100,000 times without failure;

(*d*) Low temperature testing to prove operation at, say, −65°C.

The general use of large hydraulic test rigs has enabled systems to be tested under conditions as close as possible to those in the aircraft. Fig. 8 shows a typical rig.

It is usual to carry out a large number of operations—say 10,000—of an agreed cycle, undercarriage, flaps, bomb doors, and so on. The process of development can be summarised as consisting of the successive elimination of faults.

INSTALLATION

The installation of hydraulic components on an aircraft is a difficult problem, particularly on the modern thin-winged aircraft where accessibility is poor.

Next in importance to reliability is accessibility, so that a component which becomes unserviceable can be rectified quickly. On some aircraft insufficient attention has been paid to this point.

The following examples illustrate the type of difficulty encountered:

(*a*) hydraulic selector mounted so that the engine must be removed before the hydraulic unit can be serviced.

(*b*) hydraulic pump so inaccessible that removal takes 6 hrs. work.

(*c*) valve mounted behind a control panel, necessitating the removal of engine and control cables before the valve is accessible.

Other cases occur where the location of a component leads to secondary difficulties. In one known case a hydraulic pipe was frequently flattened when nipped between a structural member and the rear end of a gun on the latter being slid into position. Other difficulties have occurred with hydraulic components so located that when removed, oil dripped on oxygen or electrical gear.

Installation is mainly a matter of common sense. Fig. 9 shows a type of installation which appeals to the hydraulic engineer.

The hydraulic designer can help by designing components so that pipe connections do not interfere with the ready removal of the units. Fig. 10 illustrates good and bad practice. Attachment brackets must be strong enough to deal with spanner loads during tightening of connections—a point often overlooked. Thin components such as accumulators must not be mounted by clamp, otherwise the cylinder may be distorted.

A difficulty arises with the installation of small components, such as non-return valves. It is usual to engrave an arrow on these units indicating the direction of flow, but often they are installed the wrong way round. It is not practicable to make the connections of different size and it is suggested that the aircraft constructor should paint an arrow on the airframe adjacent to the component to indicate the correct direction of mounting.

Similar labelling of pipes passing through bulkheads will help in tracing pipes during overhaul. Where components are installed with name plates or serial numbers hidden, the appropriate information should be shown on some conspicuous place.

MAINTENANCE

In order to simplify installation, attempts have been made to group components together, either on panels or in multiple units.

The installation of grouped components on panels may enable the whole panel itself to be removed for servicing of any item, but will probably introduce an offsetting inconvenience, as the local pipe lengths being short will make removal of the individual components difficult.

The grouping of components inside a common body may sometimes hinder maintenance. It introduces difficulty in tracing a fault and involves dismantling a complete assembly when only one item needs rectifying. For example, it may be preferable for the pump and cut-out to be separate units rather than attempt to build an omnibus assembly of these components. Pumps submerged in reservoirs, hand pumps with integral relief valves, or selectors with internal thermal relief valves, are examples of such multiple units. However, a saving of pipe connections is a factor to be considered, and the local grouping of components in a common body can sometimes be beneficial. An example of this is shown in Fig. 11 where a non-return valve is screwed into the body of a selector.

Some hydraulic components may not be readily dismantled or reassembled without special tools. Glands are frequently damaged because suitable sleeves are not utilised on assembly. For reasons of weight some hydraulic jack cylinders have thin walls and

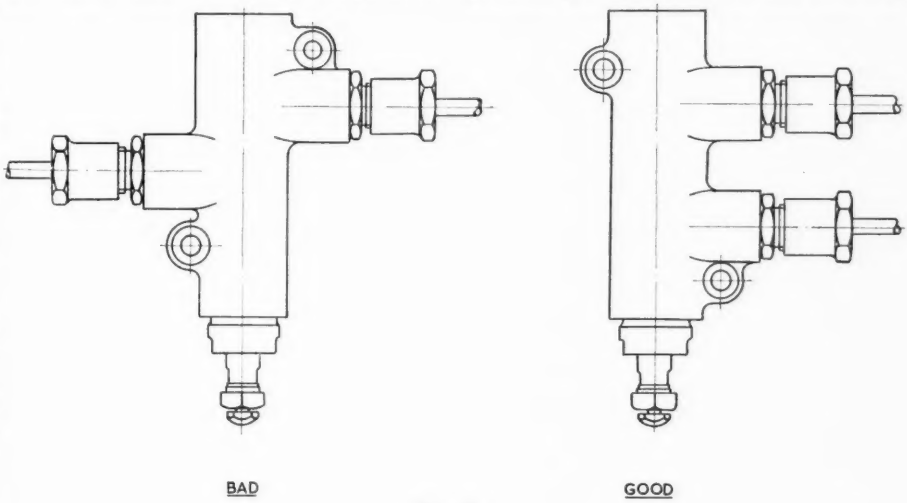


Fig. 10.
Location of pipe connection on units.

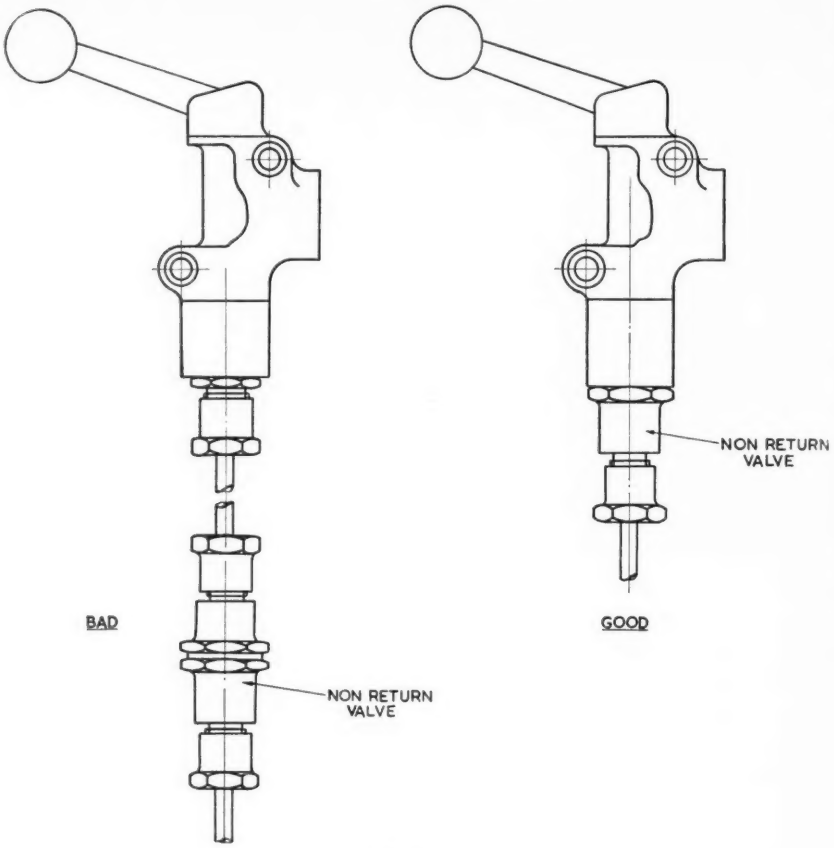


Fig. 11.
An example of integral component mounting.

these cannot be clamped in an ordinary vice but must be held on special fixtures when being dismantled.

Figure 12 illustrates different methods of attaching cylinder ends. The screwed types are preferred from the servicing aspect.

A source of unserviceability is leakage or other failure of hydraulic components, brought about by faulty or careless assembly during maintenance. Seals may be cut or twisted on assembly; copper washers fitted on joint faces which are burred or otherwise imperfect; swarf or filings allowed to enter components during assembly.

An adequate standard of maintenance can only be achieved with skilled workmanship and proper equipment.

Another source of trouble arises from dirt entering pipes left uncovered when a component is removed for servicing. Pipes should be taped or plugged when left exposed, particularly under desert conditions—surgical tape is satisfactory and readily available, but rubber plugs would be preferable.

Inflation points, accumulator or air bottle pressure gauges, should be accessible from the ground to facilitate regular maintenance. (In this connection it is worth realising that two small access panels are better than one large one so that adequate wrist freedom is allowed). It is sometimes suggested that, as manual operation of the hydraulic system is not now required, the hand pump should

be eliminated. It is, however, so vital for maintenance work that it should be retained in some location, such as the undercarriage well, where it is accessible to the ground crew.

SPECIAL PROBLEMS OF HYDRAULIC EQUIPMENT

POWER FLYING CONTROLS

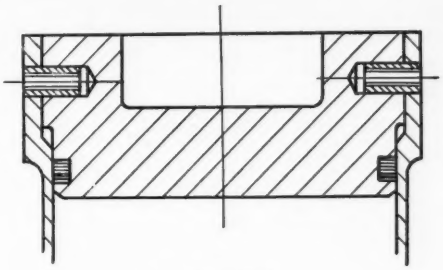
In order to guard against failure of any one part of the system it is usual to duplicate the installation completely, including the hydraulic jack units, pipes and pumps. The net result is a complex system. In the event of one system failing the other must be able to operate with the minimum delay and, in fact, it is usual to have both systems operating simultaneously. Power controls are a comparatively new development and it is not considered possible to discuss serviceability of these systems as most of them are in the early stages of development.

The degree of reliability which has already been achieved with aircraft fitted with all powered flying controls is surprising and says much for the detailed thoroughness with which the systems have been prepared. The hydraulic engineer is not able to put forward ingenious proposals which will make sure that the system is fool-proof; careful design and adequate development are essential.

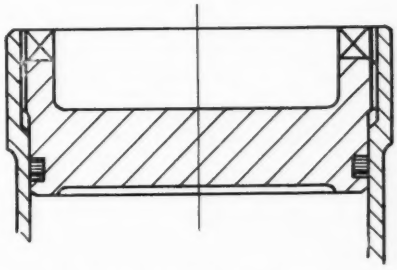
Although most hydraulic servo systems consist of hydraulic jacks operated by selector valve devices of one type or another, there are several designs of hydraulic servo which make use of hydraulic pumps of the variable stroke type, either driving hydraulic motors which then operate screw jack units, or driving directly reciprocating hydraulic jacks. While there may be something to be said for these systems from the theoretical stability point of view, they do not appear, in practice, to compare favourably with the more common type of servo jack unit fed from continuously rotating hydraulic pumps. Failures of hydraulic powered flying control systems are almost invariably due to detailed mechanical faults and the increased mechanical complexity of the hydraulic pump and motor systems would appear to aggravate the chances of mechanical failure.

ELECTRO-HYDRAULIC CONTROL

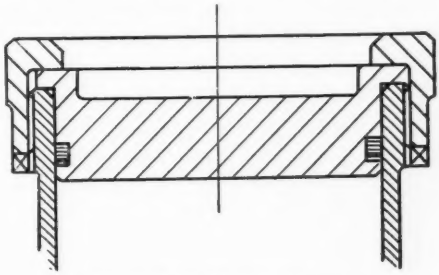
The use of electric control of hydraulic components is a necessary feature dictated by weight-saving considerations, or the need



(*a*) Dowelled.



(*b*) Threaded; seal rotated during assembly.



(*c*) Loose plug with retaining nut.

Fig. 12.
Examples of hydraulic cylinder design.

to eliminate pipe work entering pressure cabins. The need for means for operating a selector in the event of an electrical failure involves the introduction of mechanical override on selectors and this may be objectionable. Some prefer means for by-passing and over-riding the selector hydraulically. On the other hand the driving of hydraulic pumps by means of electric motors, provided that a weight penalty is not involved, is a step which will usually facilitate servicing of the aircraft and overall reliability. The mounting of pumps on engines or gearboxes usually means that they are comparatively

remote from the remainder of the system, involving lengthy pipes.

Actuator units

Proposals have been made from time to time to make use of self-contained hydraulic units equivalent to electric actuators. These consist of electric motors driving hydraulic pumps mounted with selectors on the hydraulic jacks themselves. At first sight these units appear to be attractive, but on further investigation it has been found that they have an unnecessary degree of complexity and will not, in fact, compare with a more straightforward hydraulic system consisting of a number of separate components.

The use of hydraulics in unusual applications

Aircraft designers are often tempted to make use of hydraulic control on new requirements which may arise. These new applications may often be found to be perfectly satisfactory as, for example, a hydraulic locking system for control surfaces when servo tabs are used. On the other hand, although such devices as flow dividers and flap synchronisers are known and are in production, a conscientious hydraulic engineer will not allow his ingenuity or skill to get the better of his good judgment, and would recommend such devices only for application where failure in performance of the hydraulic unit does not cause serious difficulties. There are many types of valve which perform well (the flow divider is a good example of this) but which, under certain conditions (as, for example, when an orifice becomes choked with a piece of swarf) fail to function. The use of flow dividers on wing flaps, therefore, requires careful consideration.

Both Companies with which the authors are associated have devoted much effort in developing manually - operated hydraulic remote controls. As a result of this experience, the use of manual hydraulic remote controls (for throttles and so on) is not advised. These controls can perform extremely well in the laboratory, but it has not been found possible to evolve seals which on the one hand allow the operating friction of the control to be sufficiently low not to interfere with the feel of the unit, and on the other hand prevent the slight leakage which occurs as they are operated, thus affecting the synchronisation of the control.

Hydraulic brakes

A principal reason for the introduction of the hydraulic brake is that the smallest size of operating pistons have had to be used in order that the hydraulic part of the brake does not mask or interfere with the direct air cooling of the brake discs. This has meant that brake operating pressures of 1,500 lb./sq. in., or higher, have been used in preference to the 150 lb./sq. in. which was current on the earlier bag type of pneumatic brake. It is modern practice with hydraulic brakes, particularly on civil aircraft, to require a degree of duplication of the operating system to make sure that brakes are always available. An important point which must be watched in any brake design is that there is provision for preventing oil leaking past one of the seals on to the hot brake disc surface, as a fire might result. It seems likely that automatic brake governor devices will be introduced, but it is too early to say whether these are likely to introduce complications from the serviceability point of view, or whether they will be found to be reliable. It should be possible to arrange that if they go wrong, no damage is done to the normal operation of the brake.

WHAT OF THE FUTURE?

Aircraft hydraulic equipment has become stabilised in its broad conception, although we like to feel that the ingenuity of the average hydraulic engineer, as displayed by his performance over the past fifteen years, will be continued and that he will produce further devices which will enable the aircraft designer to solve new problems. Undoubtedly hydraulic solutions will be found for means for varying wing or tail plane incidence. Hydraulic devices will be developed for producing artificial feel, for "g" restriction and possibly, for gust alleviation.

The future will bring development in ultra-high pressure hydraulic systems, although the authors are not able at this stage to predict how far the pressure may ultimately exceed the present 4,000 lb./sq. in. development. Improvements must take place in pipe material because the weight of piping on a modern hydraulic system is excessive. It seems probable that the work being done in Great Britain and in the U.S.A. in the

development of non-inflammable hydraulic fluid will eventually result in a satisfactory fluid.

It is considered that the degree of reliability which is achieved on an automobile hydraulic brake, or on a modern hydraulically-operated machine tool, is a good example of what can be achieved with properly designed and developed hydraulic machinery.

CONCLUSIONS

The performance of present-day hydraulic equipment is something of which the hydraulic engineer can well be proud. The tendency towards increased complexity of the system is the principal difficulty. To meet these problems extensive facilities are available in the industry for carrying out hydraulic development. Certainly, few sections of the industry are better equipped. The aircraft designer can do much to facilitate the overall performance of hydraulic systems by improved installations. The greatest problem which the hydraulic engineer is contesting is ingress of foreign matter into hydraulic systems.

ACKNOWLEDGMENT

The authors acknowledge gratefully the help of many friends in the Aircraft Industry, the Airline Corporations and the Royal Air Force, who have contributed their experiences and ideas.

DISCUSSION

R. S. Stafford (Handley Page Ltd., *Fellow*): He had little experience of pneumatics, and on those forms of which he had had experience, hydraulics and electrics, there was far too much trouble with both at present.

The authors had mentioned the use of electric drive for hydraulic pumps, and had suggested that servicing and reliability might be improved thereby; he thought the improvements would be substantial, especially for jet power plants, in which accessory drives presented difficult problems. Generally speaking, the duty cycles for hydraulic pumps were such that electric motors driving them could be relatively light, so that for large multi - engined aeroplanes which employed high voltage A.C. generation with D.C. rectification, electrically - driven hydraulic pumps could continue to function so long as any one alternator was working.

The use of electric drive for hydraulic pumps had important advantages in that the hydraulic units could be located from considerations of accessibility and structural or operational convenience, and long pipe runs were unnecessary. Gearbox drives were simplified or eliminated and it seemed to him that, for large multi-engined aeroplanes, that represented the optimum arrangement for hydraulic power; did the authors agree?

He agreed with the last sentence in the paper, that "The greatest problem which the hydraulic engineer is contesting is ingress of foreign matter into hydraulic systems." The use of high pressures called for fine tolerances in hydraulic equipment, and that in turn called for an exacting filtration requirement, especially when sliding elements were used. Filters to handle the maximum fluid flow without serious back pressures were likely to be bulky and heavy. Did the authors consider partial filtration to be adequate? By "partial filtration" he meant the by-pass type.

He regarded seal failures as next in importance as a cause for unserviceability; and while some seal failures could be attributed to dirt, the majority were probably attributable to other causes, such as faulty assembly, or unsuitable material. That, again, might be due to poor detail design, and he agreed that "Modern systems demand skilful design if reliability is to be achieved."

The slow rate of progress in the development of a satisfactory non-inflammable and non-toxic fluid was disappointing. Apart from the obvious advantages, in those cases where hydraulic pipes must enter the cabin, design and maintenance were made more difficult because ducting of fluid pipes was desirable and accessibility was often made difficult because electric cables must be kept clear of fluid pipe lines. Would the authors prophesy when a suitable fluid would become available, non-inflammable and non-toxic?

Brief reference had been made to operation at low temperatures, and designers were much exercised over problems associated with high viscosity. It would appear that

certain hydraulic installations would demand local heating to ensure reliability of operation under intense cold; alternatively, certain circuits might be arranged for self-heating. Bearing in mind that existing flexible hoses became almost rigid at temperatures of about −30°C. or below, he was interested in the diversity of views held by the respective lecturers on the subject of flexible joints. Would the authors indicate how they would propose to overcome that difficulty?

Handley Page Ltd. had had little trouble with a standard clipping pipe length of 20 in.

B. S. Shenstone (British European Airways, *Fellow*): The authors had referred to the complexity of new aircraft; recently he had read about an aircraft firm building such complicated aircraft that they had to use punch card equipment in order to keep a continuous check on the location of various pieces of equipment to avoid putting more than one piece in a given place. It was necessary to stake a claim when the aircraft was in an early stage in order to get ahead of the other man!

He was concerned with an airline which operated older aircraft because they could not yet afford new ones. Judging from what the authors had said, the Viking should be more difficult to deal with than the Dakota; but apparently the Viking was the simpler, because in the course of three months' operation on 30 Dakota aircraft there were about 70 hydraulic defects, whereas in 40 Viking aircraft there were only 36 such defects.

Over the same period, in the Dakotas the electrical defects were about one-and-a-half times the number of hydraulic defects, whereas in the Vikings the number of electrical defects were five times the number of the hydraulic.

Air Commodore Silyn Roberts (*Associate Fellow*): He tried to avoid making comparisons between electrical and hydraulic methods. A conference had been held on the subject in the Ministry of Supply during the 1939-45 War, and rather than attempt to answer the conundrum himself, he had asked one of his staff to go to the United States to find the answer; on returning to Great Britain he had said, in effect, that there was no answer.

G. H. Dowty (Dowty Equipment Ltd., *Fellow*): He emphasised the great importance of the efficiency of the pumps supplying fuel to jet turbines; the American fitted two pumps, so that if one failed they could use the other. On certain well-known types of engines built in Great Britain, there was only a single pump, and it appeared necessary to provide good filtering.

To his surprise, the Americans had decided to provide no filter before the pump. To prove that it was not necessary, in one case they had put 80 c.c. of desert sand into a tank and had run the pump for 100 hours, and the result had been a reduction of only 21 per cent. in performance. It was gratifying to realise that the users of complex units could operate these without the use of filters, but he was not suggesting that filters should not be used.

R. H. Chaplin (Hawker Aircraft Ltd., *Fellow*): The failure of pipes at the joints was a most important, yet not easy, problem to solve. One difficult matter was to determine whether a pipe had been clipped too rigidly or whether it had not been clipped sufficiently and was thus allowed to vibrate. Could the authors give advice which would help to determine which of those two possible defects was responsible in the event of failure?

Two suggested types of pipe joint had been shown, but he thought the best results would probably be obtained from a combination of the two. The second proposal was a flexible joint, the pipe being merely pushed into position and held by the attachment of the end connections to the structure. That looked nice in a small diagram, but he felt that in a comprehensive system it would not be quite so practicable. A rubber-sealed joint should be good, for it would do much to relieve the joint of the bending stresses which he felt sure were largely responsible for failures at that point. Could they not have a joint with a flange and with a rubber seal held in position by a gland nut?

So far no one had mentioned the main difficulty of filtration, as he saw it, namely that there was no real circulation taking place at all; in most of the hydraulic systems there was a reciprocating motion of the fluid which prevented it passing continuously through the filters. Could the authors say more about the introduction of filters on selector valves, which were particularly prone to that sort of trouble?

V. A. Higgs (British Thomson-Houston Co. Ltd., *Associate Fellow*): He agreed on

the necessity for giving time for development. If they took away from any modern aircraft all the hydraulics and all the electrics, they were left with a useless metal box fitted with equally useless engines. In view of this it was really important that time be allowed for the development of hydraulics and electrics to their fullest extent, and those concerned with such development should be given as much time as was given to the development of the aeroplane. In other words, they should be consulted at the beginning.

It was fortunate that their industries were still in the hands of private enterprise. Those concerned with electrics tried to do better than those dealing with hydraulics, and *vice versa*, and the electrical firms themselves vied with one another. Ultimately this reacted to improve both electrical and hydraulic equipment.

A fortnight before, Mr. Woodall and he had given a paper on electrical serviceability and had spoken on behalf of the entire electrical equipment industry; their "non-aggression pact" was now over.

Mr. Stafford had asked about the size of motor to drive a pump; the motor had not only to provide the output of the pump, but to overcome all the losses in the combination.

What was being done in Great Britain to provide a non-inflammable fluid for use in hydraulic equipment, and when would it be available? Apart from the obvious safety aspect, he had a somewhat ulterior motive at the back of his mind. He imagined that the authors considered the ideal aeroplane to be one operated entirely by hydraulics, but even in this aeroplane they would allow the radio equipment to be operated by electrics! Thus probably there would be a motor generator, which would find itself parked alongside a hydraulic cylinder or pipe which was bound to spring a leak at some time or other; therefore, the machine had to be made flameproof. A fine gauze had to be fitted over each air opening, which seriously handicapped the cooling and made the machine bigger. Because of leakage from the pipes, the atmosphere would be oily, and oil would be deposited on the gauze. There was usually dust about and eventually the machine would become, in effect, totally enclosed, so that it might become hot and ultimately catch fire. Thus, the very thing that was put on to the electrical machine to prevent explosion was likely to cause fire. that was a serious problem. One solution might be to ask that the hydraulics be kept away from the electrics; but he was not sure whether that could be done. A much better solution would be the use of non-inflammable fluids.

Anything could be proved by statistics; but Mr. Shenstone's remarks about defects on the Dakota and Viking were a little too casual, and they wanted to know much more about the matter. What did those failures mean? The matter had to be put in terms of the number of hours of work required to put things right. A wire might be pulled off causing no harm or damage and it would be reported as an electrical failure; but it did not take long to put the wire on again. He was not sure that the Viking was an aeroplane which those in the electrical industry would quote as a good example. It was developed quickly after the war, using a lot of equipment which was developed during the war under rather difficult conditions. Bearing that in mind, it was a very good aeroplane and had given remarkably good service.

Contributed: He would like to elaborate on the combination of electric motor and hydraulic pump. Assuming a pump efficiency of 80 per cent. and a motor efficiency of 70 per cent. the motor input would be nearly twice the pump output. That could only account for part of the difference in weight and size of the two components and, for some time now, he had been puzzled as to why there was this great difference in size.

The requirements of the two components were in opposition since it seemed that the pump required a low speed and a high pressure whereas the motor preferred a high speed and a low pressure (electrical). On 1st March he had helped to try to convince the Aircraft Industry that efforts were being made to keep the size of electrical equipment to a minimum and in motor/pump combinations they had great difficulty in dissipating the losses as heat from the surface of the electric motor, big as it was. For altitude operation it was almost inevitable that forced cooling would be required. He wondered how the losses in the hydraulic system were dissipated and could only conclude that the fluid was a good conductor of heat and that the surface area of all the pipes, accumulators and other equipment assisted in the cooling. That, he felt, was a fundamental advantage of hydraulics because in an electrical system

the conductors had to be covered with an electrical insulator which was also a good heat insulator. That advantage, apparently, could be embarrassing in some installations, because mention had been made of the difficulties of low temperature operation and the possible need of heating the fluid.

With only a limited knowledge of hydraulics to guide him it was his opinion that, at present, electrical power could not achieve as low a weight as hydraulics for the provision of a direct straight line thrust. He said this for the reasons already given and because mechanical power from lightweight electrical machines was obtained as a high speed rotation and not as a low speed push.

Electrical power did win in the ease with which it could be delivered to any part of the aircraft, over the most tortuous of routes, and also the comparative ease by which it could be controlled by safety devices. Faulty sections could readily be isolated and if the service were an essential one alternative circuits could be provided. With hydraulics the provision of alternative supplies led to much greater complications. It was his opinion that for an involved mechanical power system a combination of electrics and hydraulics, taking the best from each, would give the lightest overall weight with the maximum of safety and reliability.

C. B. V. Neilson (Electro-Hydraulics Ltd., *Associate Fellow*): In the paper there appeared to be remarkably little comment on seals and piston rings. Having had considerable experience of a number of types of rubber seal, including those shown in the sectional drawings in the paper, he would have thought that their improvement should have been one of the first targets of hydraulic designers in progress towards hydraulic serviceability. In particular, remarkable claims had been made for "O" rings of the American type, and it was understood that the twisting difficulties which were experienced with them in Great Britain at one time, had been overcome. As one of the authors was associated with a firm now manufacturing those rings, it would be interesting to have his unprejudiced views on how they compared with English types of seal.

Another type of unserviceability which was not mentioned was mechanical failure. Perhaps the authors had taken the view that that question was too elementary, the answer being simply to design things with greater strength. But the strength of the components must deal with both the maximum load reached in service and with the repeated loads applied, and with hydraulic equipment every application of load might be a maximum load, if it were imposed by the pressure of the system. Thus, hydraulic equipment was more susceptible to fatigue failure than was any other type of airframe equipment. For example, there was a ring nut which was similar in design and application to that which secured the jack end fitting in Fig. 4, and which had failed in service. On strength test it was found to have an ultimate strength equivalent to four times the hydraulic relief pressure, and yet on fatigue test it withstood only 12,000 operations. Failure resulted due to cracks in castellations of the nut in spite of the fact that they were well radiused. He had come to regard such castellated nut designs as a number of segments of superfluous material joined together by stress concentrations !

The fatigue life of hydraulic equipment was aggravated if continually pressurised systems were used, for whenever any service was operated, the pressure throughout the system was liable to be reduced to something approaching tank pressure and built up again to cut-out pressure; thus, a component which was used only once per flight might be pressurised about ten times. With a system which was neutralised after operation the components were loaded only when they were actually operated.

That fatigue question had recently received general recognition so far as light alloy components were concerned, but in some cases, such as the ring nut he had mentioned, which was in S.11, steel components were also suspect.

For combat aircraft, fatigue life was perhaps comparatively unimportant, but for civil and service transports it seemed to be a point which should receive full consideration. He would welcome the authors' views on the subject.

R. H. Woodall (Rotax Ltd., *Associate Fellow*): Electrical and hydraulic engineers had several common problems, and one of them was that of providing efficient seals. What was the experience of the authors of the Silastic rubbers which had been much advertised in America and which he believed would be made here in the near future? His Company were embarking on some development work with those seals.

The other problem was lubricants and there was a difficulty in providing a lubricant which would effectively cover the wide temperature range now being specified for both hydraulic and electrical equipment.

With certain types of actuators, it might be necessary to keep their temperature above the limiting temperature of the lubricant to ensure satisfactory operation after prolonged soaking at −90°C.

A. Kenneth Clyde (*Associate Fellow*): Had the authors considered the type of jack, using an electric motor with the pump built in on the jack? It seemed to him that the vulnerability of such units from the military point of view was important; this arrangement reduced vulnerability as it involved no pipes.

If the self-contained actuator unit were better than a system of separate units, why was it not used?

S. M. Parker (Automotive Products Co. Ltd., *Associate Fellow*): Serviceability or reliability was about the most important question for the hydraulics specialist, and he suggested that the reason for the 99 per cent. usage of hydraulics was fundamentally the realisation of that fact by the users.

One major quarrel he had with the authors was that the gap between theory and practice was much bigger than might perhaps be gathered from their paper, particularly if one were not familiar with the industry from either the supply or the users' end. It rather painted a picture of a number of small detail faults which could not be eliminated even by the universal adoption of the practice of subjecting a sample of every piece of equipment to 100,000 operations before it was fitted to an aeroplane.

He hoped he would not be considered unduly cynical if he suggested, in regard to the plea that the aircraft manufacturers should bring in the hydraulic equipment manufacturers at the beginning, that that would not help much. In cases where there had been a real attempt to do so, it was not entirely successful because it did nothing to cover all the troubles which still occurred at a later stage. He pleaded for the acceptance by the Industry of the fact that probably about 50 per cent. of any hydraulic system in an aeroplane was fundamentally new and needed development before it was used, and he asked the Industry to refrain as far as possible from altering at the last moment just those things which were most important. They should balance—and only they could do it—from the point of view of the good of the aeroplane as a whole, whether to tear up completely a complicated mechanical job or whether it was better to alter the structure of the airframes. The specialist suppliers would abide by their decision, if they could feel that the matter had been looked into in that way, but he was not quite satisfied that that had always been done in the past.

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It seemed that there would be some difference between military and civil aircraft in that respect, because he believed that in the military aircraft a large part of the problem arose from the disposition of military equipment, which often had to be changed during the design of the aircraft, or varied with the various Marks, which might number as many as 14. Those changes invalidated a lot of the elaborate rig testing which, as the authors had said, represented an important part of the development of hydraulic systems.

He supposed that power-operated controls represented probably the most important application to which any service in an aeroplane could be put. From the remarks made in the paper, under the heading "Lines of Improvement," it seemed that the problem of using higher pressures was bound up with the difficulty about hydraulic seals. The authors had stated that: ". . . there is not much advantage to be gained in raising pressures of a system which is in continuous operation, as for example on powered flying controls operating at 3,000 p.s.i. There is, however, everything to be gained on large aircraft in raising the pressures on the remainder of the system to 4,000 p.s.i. or even higher." He felt that the construction which could safely be put on that statement

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C. G. A. Woodford (*Associate Fellow*): The chief problem in the hydraulic system was the installation of the pipes, and so forth. On that hung a lot of the difficulties from the points of view of the supply and the development of hydraulics, the installation of the system by the aircraft maker and its maintenance in service. Mr. Clyde had gone some way on that matter when referring to electro-hydraulic as against electro-mechanical actuators, and the authors had gone some way in recognising the great advance that could be effected in driving the pumps electrically.

It seemed that there would be some difference between military and civil aircraft in that respect, because he believed that in the military aircraft a large part of the problem arose from the disposition of military equipment, which often had to be changed during the design of the aircraft, or varied with the various Marks, which might number as many as 14. Those changes invalidated a lot of the elaborate rig testing which, as the authors had said, represented an important part of the development of hydraulic systems.

He supposed that power-operated controls represented probably the most important application to which any service in an aeroplane could be put. From the remarks made in the paper, under the heading "Lines of Improvement," it seemed that the problem of using higher pressures was bound up with the difficulty about hydraulic seals. The authors had stated that: ". . . there is not much advantage to be gained in raising pressures of a system which is in continuous operation, as for example on powered flying controls operating at 3,000 p.s.i. There is, however, everything to be gained on large aircraft in raising the pressures on the remainder of the system to 4,000 p.s.i. or even higher." He felt that the construction which could safely be put on that statement

was that, the less the system was used, the better; in other words, the aeroplane had to carry around a weighty installation with all its elaborate pipes, fittings, and the rest for a limited amount of utilisation. Practically speaking, in the electrical system there was a much higher utilisation of many of the various services, and he believed that difference represented much of the background in making a choice of system at the present time.

On the point that 99 per cent. of aircraft used hydraulic systems, was it not largely because 99.9 per cent. of aeronautical engineers were mechanical engineers—and what they knew was always better than what they did not know? He imagined also that they would not have widespread main line railway electrification in Great Britain until the race of steam engineers had died out.

With regard to motor drives with hydraulics he suggested, in view of the great number of pumps now becoming necessary, there might be a possibility of coupling two pumps to one motor in some cases. In one of the largest aeroplanes yet built he believed it was proposed at one stage to take away the large number of pumps from the engine gearboxes and connect them to motor drives. It was then found that, although the adoption of that proposal would save weight and losses in flow, the entire system could not be cooled without the mass of pipes and the oil, and they had to be put back, thus adding to the vulnerability and maintenance of the aeroplane.

W. G. Lisle (Fairey Aviation Co. Ltd.): What were the authors' opinions on what could be done to remedy the difficulty of under-developed components and systems on prototype aircraft?

Was the solution to be found in a greater realisation of the processes involved and, therefore, considerably intensified development effort during the period of aircraft prototype design and construction, or should all novel and experimental components and systems, critical to flight operation, be proved in specially allocated flying test bed aircraft before being approved for installation in new aircraft types?

G. J. Armstrong (*Associate*): He referred to the simplicity of centrifugal pumps and asked why they could not be used. Also, he criticised the tendency towards increased complication.

K. G. Hancock (*Associate Fellow*): From discussions with aircraft service and maintenance engineers it was apparent that hydraulic leakage past seals was one of the most frequent troubles experienced with aircraft hydraulic systems. The use of high tensile steels with greater material stresses gave increased clearances under working pressures and that, together with the necessity of high operating pressures, had made the problem of seal design difficult. He felt that the employment of metal rings on pistons when a small leakage could be tolerated, and also on piston rod seals with a rubber or fabric seal at tank pressure to prevent external leakage, was an attractive solution. Tests had indicated that the leakage past such seals could be small and an improved life was obtained.

From Fig. 4, the difficulties of ensuring a satisfactory lock indication with internal lock jacks were appreciated. Was it not possible that such an arrangement could be made simpler and more reliable by registering only the position of the lock bolt at the jack, with a separate switch in series on, say the radius rod, to indicate the safe landing position? That, admittedly, involved a greater amount of electrical wiring, but avoided the use of seals on the switch mechanism at the jack. Such an arrangement was used successfully on the Halifax and he felt that the registering of both conditions at the jack with one switch was of doubtful advantage. He might have misunderstood the diagram but it appeared that failure of the seal in the switch would give a false locked indication to the pilot. This might be disconcerting if, as was likely, the seal failed on selecting undercarriage up.

The question of a failure of one part of the system affecting other parts, such as loss of oil through broken pipe exhausting the reservoir and putting the complete system out of action, was of importance. The policy of using neutralising selectors allowing circuits to remain at tank pressure between operations seemed to be advantageous in that respect. It could only be applied, however, when the services operated were held by mechanical locks at their extreme positions. It would seem worth including, say an internal jack lock in a circuit not normally requiring a mechanical lock, so that pressure release between operations could be employed. He believed that that release of pressure between operations was a require-

ment in the United States for military and civil aircraft.

J. A. C. Manson (*Fellow*): He referred to the reliability and serviceability of hydraulics from the particular aspect of the possible deterioration of hydraulic components held as spares, either due to the storage of assembled components in which the seals might suffer from drying out, or by the storage of hydraulic jack and oleo legs on their sides improperly supported, when the seals might become distorted and so suffer from leakage when put into service. They had experienced this sort of trouble and he wondered what was the experience of the authors in this direction.

N. J. Hancock (*Associate Fellow*): Did the figure given by the authors of 30 per cent. of the weight of an aircraft hydraulic system being due to the pipes take account of the weight of the oil contained in the pipes? He asked because of the never-ending argument on electrics *versus* hydraulics, and he wondered whether all the weights involved were considered.

What was the weight of the generator required to feed the motor to drive a hydraulic pump and was that taken into account?

Was not most of the trouble experienced with joint failures due to lack of flexibility, or rather, too rapid a change of flexibility, rather than rapid change of section where failures occurred towards the flare?

Had the authors done any research on the pipe joint system that was popular years ago on American cars, where they had used a comparatively soft metal olive and had squashed it up on to the pipe, causing a certain amount of restriction in the pipe? It appeared to have given satisfaction.

During the 1939-45 War there had been an epidemic of joint troubles due to crossed olives. Therefore, he had been interested to see the authors' illustration of a new American joint, and he wondered what were the prospects of a joint of that sort being adopted generally in Great Britain?

A Speaker: Had trouble been experienced because of electrolytic action between dissimilar metals at places such as pipe joints, the hydraulic fluid acting as the electrolyte?

Also, had sudden changes of pressure through valves caused cavitation and erosion of valves, or pipes, or the hydraulic pressure containers?

F. W. Kennedy (*Associate Fellow*) *contributed*: He endorsed the emphasis that the lecturers placed on the effect of "dirt" as the most common cause of unserviceability and incorrect functioning of hydraulic systems. Practically all the usual functional faults in service (sometimes apparently complex) had this as their primary cause.

He did not agree that the methods adopted to combat this menace were necessarily correct and queried the implication that a hydraulic system manufactured its own "dirt." Certainly any micronic dust which might be manufactured by the system was insignificant in comparison to the pipe swarf and extraneous "dirt" which gained access.

He suggested attention to the following points:—

(1) *Pipe swarf*—having taken such extreme care in the design, manufacture and testing of the precision-made components, was it unreasonable to expect the installatain link-up to be clean and swarf-free? *Remedy*: clean the pipe-line and joints as thoroughly as a slide valve and its platens would be cleaned. The onus there was on the airframe manufacturer.

(2) *Extraneous dirt*—the fitting of shrouds or stockings to every unit of the system exposed to outside contamination (not just mud from the wheel-bays) was a requirement which was too often overlooked.

(3) *Dirty fluid*—He did not believe the "dirty can" business was really as common as popular opinion would have them believe. Certainly the open header tank was an undoubted point of entry for extraneous "dirt." By all means seal the system and introduce filtered fluid with an oil gun and perhaps they could stop the use of incorrect fluids by the simple device of fitting different oiling nipples.

The difficulty there was a service one—special tools. No one would dream of putting unfiltered petrol or engine oil into an aircraft, so why should there be unfiltered hydraulic fluid? The present filter neck strainers were not the answer.

He suggested that the present trend of internal filtration at every vulnerable point in the system was wrong and unnecessary. Make a clean system (no dirt, no swarf), use every device to keep it clean (external filtration and shrouding) and this would eliminate the major source of hydraulic unserviceability.

REPLY TO THE DISCUSSION

MR. CONWAY

Mr. Stafford: The big difficulty with electro-hydraulic drive was the weight of the motor required to drive the pump. In one case the motor was nine or ten times the weight of the pump it was driving; and the problem with regard to bulk was even more serious. If they could secure agreement on a suitably short rating for the motors, he believed the electric drive would be more widely adopted. If it enabled the users to eliminate accessory gearboxes, that was another advantage, because the weight saving that could be effected there was considerable.

An interesting new development involved the use of a filter with a sintered bronze element which was so cheap that it could be thrown away; if they could obtain designs of filters which would last only 30 hours, and if they were cheap, they could afford to use them expendably. At present, filters were designed to go a fairly long time between cleanings, and that was one reason why they were so large.

He did not like by-pass filters, because they wanted to prevent dirt getting into components completely rather than to eliminate it gradually. Even one piece of dirt might do damage.

The industry was conscious of the need for better seals and was endeavouring to provide them. One of the difficulties in Great Britain was that the rubber materials available were of certain types made in America; they were rather limited in that respect. That was the answer to the question concerning the flexible joint; the seal was just as difficult to operate at −30°C. as was the flexible pipe.

Low temperature operation was indeed a problem. A difficulty was that no hydraulic engineer had been told yet how cold a system would become in flight. There had been rumours of certain aircraft which remained warm in flight. There were several means of heating; the best method was not necessarily hydraulic, and there were some electrical methods which might be used.

Mr. Shenstone: Mr. Shenstone's remarks seemed rather a sad comment on the reliability of electrical systems. He was interested to note that there were more hydraulic defects on the Dakota than on the Viking, and would be interested to know something about the types of failures that had occurred, for one of the great difficulties was to obtain this type of information. The comments on the comparison between electrics and hydraulics were not really valid, because the actuating electrical systems on those aircraft were not extensive.

There were many things in aircraft which they could not avoid fitting, and he was afraid that complication was just one of those things that had to be accepted; the whole aircraft was becoming more complicated, and presumably that meant that they would not be able to make so many of them.

Mr. Dowty: He supposed that ultimately they would hope to be able to design components which would run on dirt! That might sound facetious, but if they knew how to do it they would like to design things which would run even if there were handfuls of sand in them. Some precision pumps could operate after 80 c.c. of sand had been added to the liquid in them, because the clearances were so fine that the grains could not get in; but where clearances were such that the grains could get in, so that they scratched the cylinders, the best means of tackling the problem was to provide protective scrapers. But there were "micronic" dirt particles which would enter even into very fine clearances, and they might have to be eliminated.

Mr. Chaplin: Both Mr. Bound and he had been under the impression that it was good practice to clip pipes rather on the lines suggested in Table II, and they liked the type of clip made with a lining of rubber to give a certain amount of elasticity. One company, as the result of recent work, had concluded that that might not be the best, that it might be better in certain cases to allow a certain amount of flexibility. But the matter depended on the amount of structural deflection at certain places, and it was difficult to be categorical.

They had thought of a joint in which the sealing was done by the rubber, and the clamping was effected by a nut. In other words, it had not to be screwed up very tightly to effect the seal.

There were many pipes in which the oil moved backwards and forwards, and that was the reason for fitting local protective filters. The same argument should apply to nearly all components having valves in them. They were working on the development of a

small type of filter unit which did not take up too much space.

Mr. Higgs: Neither Mr. Bound nor he wanted to give the impression that they were complaining of the lack of time they were given by their aircraft friends to develop the hydraulic equipment. They realised, perhaps better than did the electrical industry, that accessory equipment was something which was always treated at the last minute, and probably it would never be otherwise. They merely asked their aircraft friends to give them a few months in which to sort difficulties.

He was not sure that the pump motor which was referred to as being nine or ten times the weight of the pump was one for which the honourable member for Cricklewood was responsible, but the one for which the honourable member for Rugby was responsible was twelve times as heavy as the pump !

As an electrical engineer, Mr. Higgs had disclosed notable ignorance on elementary hydraulics ! Hydraulic pumps were efficient, well over 80 per cent. It must not be thought that most of the power was used to turn the pump round; it was doing useful work.

Mr. Higgs had mentioned radio and at last there was a "hydraulic radio." In the research department of an American university last November he had examined an ingenious hydraulic valve for a certain type of aerial weapon. It was so sensitive, the input was so small and the magnification so great that they had connected a loud-speaker diaphragm to the end of a hydraulic jack, put a gramophone needle on the end of the pilot valve and put that on to a record; and it played music !

He could not answer the question concerning the advent of non-inflammable hydraulic fluids; he did not know when there would be one. There were already viscous fluids used in the United States which were of equivalent performance to obsolete D.T.D.44, but there was no sign of a non-inflammable fluid of equivalent properties to current hydraulic fluids. Those which had been put forward so far were expensive, or too heavy, or had seized up the pumps with notable rapidity.

They could only agree, in the main, with Mr. Higg's well reasoned argument in his written contribution.

Mr. Neilson: He could not comment on "O" seals.

He agreed that mechanical failures did occur. The authors had not intended to give the impression that the only types of troubles experienced with hydraulics were those listed in the paper; they were just the fundamental troubles, and even the best aircraft firms made the same mistakes as others. It had been suggested in the paper, under the heading of "Development Technique," that the correct development technique on a rig was to go through 100,000 operations without failure. That was the sort of thing that should be done on a proper rig, and it would find out any of the fatigue failures likely to be encountered. Certainly 100,000 operations was good enough for anything except, conceivably, flying controls.

MR. BOUND

Mr. Neilsen: His Company had used a seal with "O" section sealing rings, but did not use them in all cases. It was found advisable to support them on either side by a disc to prevent extrusion of the rings, the disc being usually of leather, suitably treated. In certain circumstances they had found "O" rings to be advantageous for static seals. Jacks produced by his Company employed piston seals of square section, backed up on either side by a cast iron ring.

MR. CONWAY

Mr. Woodall: Sealing problems in electrics were not the same as those arising in hydraulics; Mr. Woodall was concerned with rotary seals, and the only application of those in hydraulics was on pumps. On modern hydraulic pumps there were no less than three seals, a fact underlining the difficulties involved.

So far, silicone rubber did not seem to be altogether suitable for some fluids. One of the difficulties with electric motors was their operation at low temperatures; the problem was to find a grease which would operate at $\pm 90°$. Perhaps the silicone greases provided a line of approach there.

Mr. Clyde: There was a statement in the paper, under the heading "Actuator Units," concerning proposals to use self-contained hydraulic units equivalent to electric actuators, and consisting of electric motors driving hydraulic pumps mounted with selectors on the hydraulic jacks themselves. But such units had an unnecessary degree of

complexity. Both Mr. Bound and he had made complete design studies.

It might be better, in certain cases from the point of view of weight than a system consisting of separate components, but it was invariably bad from the point of view of bulk and inconvenient shape.

Mr. Woodford: The remarks about higher pressures for flying controls were interesting, but the hydraulics were merely multiplying the force produced by the pilot, so that they were not concerned there with very large forces. The largest force he had ever heard of on a power control was 12,000 lb., but that was exceptional; the load on the ordinary flying control unit was probably 3,000 lb., and there was no particular advantage in going to high hydraulic pressure in any ordinary aircraft.

On the point that, the less a system was used, the better it was, he agreed that the hydraulic system was one having a low power factor. He believed that in the typical bomber the retraction time was five seconds; 30 h.p. was provided, but it was used for only a short time. The point was whether or not hydraulics provided the best means of doing that job.

The driving of three pumps by one motor had been proposed, and it had saved a little relative gearbox weight. The main point was to eliminate engine accessory gearboxes. In one case, for driving a pump weighing 8 lb., the motor weighed nearly 80 lb., and that could only be justified if some other saving could be made.

Mr. Lisle: He did not think there was any one answer to the problem. There were cases in which at the last minute somebody wanted something changed and there was no time available in which to develop the replacement. The function of the aircraft man was to get the machine flying. He did not think flight testing would be of much use for such equipment owing to the practical difficulty in doing intensive testing of occasionally used equipment in flight. If a moving tailplane were required, the hydraulic manufacturers could be asked to build a rig; if the hydraulic control would work with a particular stroke and size, it would work equally well with a little bigger stroke when fitted to the real thing. However, the hydraulic manufacturers should be given ample notice of new demands, so that they would have the chance to do some advance testing, not presented with the requirement five or six months from the first flight date.

Mr. Armstrong: They could get centrifugal pumps for up to about 1,500 p.s.i. But it must be remembered that any centrifugal pump had low efficiency, and that was reflected on an aircraft hydraulic system in terms of heat; they might get 30 or 40 per cent. of the power as heat, and the system could not stand that.

It was easy to criticise systems on the grounds of their weight, and to say that all the equipment that was put into aircraft was a nuisance. But it was no use giving the R.A.F. aircraft which were not competitive; on the other hand, it was no use putting their heads into the sand and saying that the systems were too complicated. The point was that they could not have first class machines, every day becoming more complicated for perfectly good operational reasons, and keep the weight down; weight was the price that had to be paid for what they were getting out of the aircraft.

Mr. K. G. Hancock: The use of two switches instead of one was not a practice he preferred because he believed that switches were probably less reliable than the mechanical device shown in Fig. 4.

Mr. Manson: There was no general answer to his question at the moment. At times during the war certain components had had to be removed every month or so, to ensure that the parts were not bonded; if they were left for several months they would stick up. In one case, as the result of optimistic planning, an aircraft firm had asked for materials much too soon, and corrosion had occurred in finely-fitted units. Gumming up during storage could occur quite easily.

With regard to compression strains on seals, the best answer he could give was to suggest using better types of rubber; but that was a slow process. He could not see any signs at present of a major improvement in the types of rubber, because they were made of the same basic materials as were used during the last war, and they were likely to have to continue using them for some time.

Mr. N. J. Hancock: The weight figure of 30 per cent., representing the percentage of the weight of the pipes to the total weight of an aircraft hydraulic system, did not include the weight of the oil in the pipes; it was the weight of the pipes, pipe connections and

clips associated with them. The figure was quite genuine; there were several different sources for it. The figures ranged from 20 to 33 or 34 per cent. on a complicated machine.

Pipe failures were due mainly, he believed, to the fact that the end of a pipe was belled out, and at the neck there was a concentration of stress; that particular part of the pipe was doing all the work, because in practice there was a clearance between nut and pipe. The authors felt it would be of advantage to provide a better radius here, or some other improvement.

The integral olive was introduced about 1944 in order to avoid the trouble experienced with the crossed olives. The new joint shown in Fig. 5(*a*) had been discussed by the S.B.A.C. Hydraulics Committee, and had got to Farnborough.

The weight of the generator was rarely taken into account by the electrical engineers!

It was stated in the paper that the compression olive type connections were still used in France. They had also been used widely on the Halifax. But that joint was not a very good one; it was too easy to screw the joint up too far and to over-neck the pipe, so that it was a bad joint in the hands of the ordinary R.A.F. mechanic.

A Speaker: The authors had no knowledge of electrolytic action having occurred. It might have happened, but it had not been a serious source of trouble.

There had been a little trouble with cavitation some time ago on a particular type of relief valve owing to excessive velocities, the seat being too small for the work it had to do; that was the only case he knew of a seating eroding away. Hardened seats gave a reasonable life from that point of view. A lot of trouble had arisen from shock loads, which were shown up in the systems due to the excessively rapid opening of valves.

Mr. Kennedy: If the aircraft manufacturer and operator could really ensure entirely clean systems, built-in filtration would be unnecessary; but this was unlikely and indeed impracticable. A reasonable standard of filtration seemed a reasonable compromise; the weight and cost penalty was small. Micronic filtration was a special requirement, as mentioned in the paper.

1951 GARDEN PARTY

THE Twelfth Garden Party to be given by the Society was held at White Waltham Aerodrome, near Maidenhead, on Sunday 6th May 1951, and was attended by some 3,500 members and their guests.

Unfortunately the weather was unkind; it was cold and mainly overcast, and windy.

One of the high lights of the Flying Programme was a gliding demonstration by Mr. F. G. Irving, a Graduate of the Society. This was the first time the Graduates had taken an active part in the Garden Party.

The Garden Party began with the arrival by Westland-Sikorsky S.51 helicopter of the President of the Society, Major G. P. Bulman, C.B.E., F.R.Ae.S., accompanied by Mrs. Bulman. Members and their guests were then received by the President and Mrs. Bulman at the President's marquee.

White Waltham aerodrome was again made available to the Society by kind permission of Sir Richard Fairey, M.B.E., Hon.F.R.Ae.S., and the Ministry of Supply, to whom the Society is greatly indebted.

The Council is particularly grateful to Sir Richard Fairey, M.B.E., Hon.F.R.Ae.S., Past-President of the Society, and to the Directors and Staff of the Fairey Aviation Co. Ltd., for their constant practical help over many weeks with the organisation and arrangements on the aerodrome for the Garden Party.

The Council also wish to thank the Ministries of Supply and Civil Aviation, the Air Ministry, and the Royal Air Force Balloon Unit, Cardington, and the London Air Traffic Control Organisation for their co-operation and assistance. The work of the R.A.F. Balloon Unit, Cardington, who supplied the Cody-type kites, the R-type observation balloon and the spherical balloon, was particularly appreciated. The low cloud and wind unfortunately made it impossible to demonstrate the spherical balloon, a great disappointment to many present.

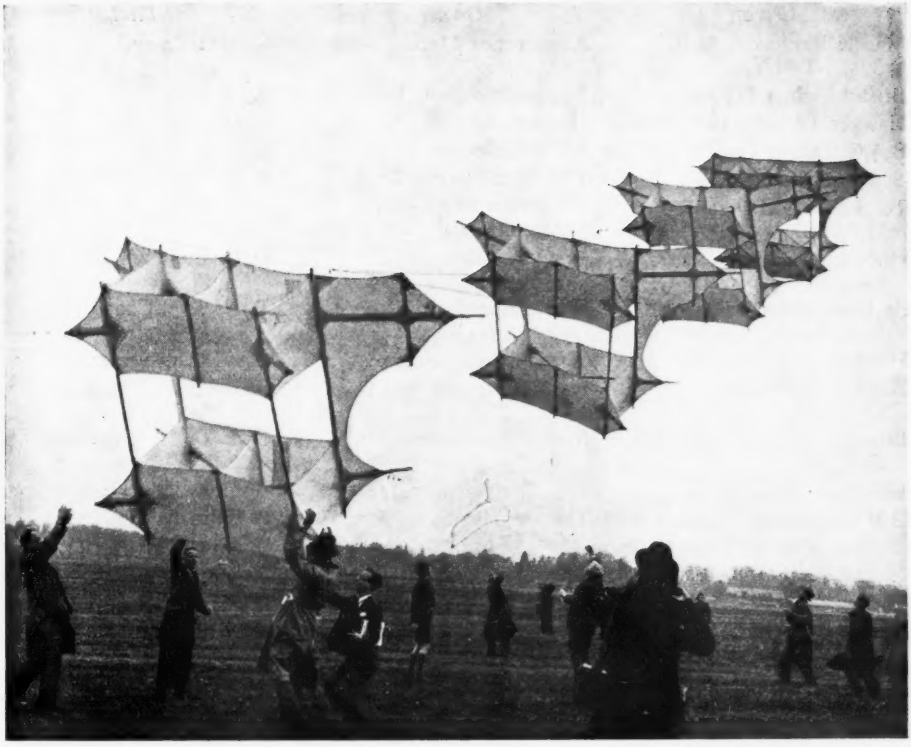
The Council also thank the West London Aero Club and the Reserve Command, Royal Air Force, at White Waltham, for their co-operation.

Flight

The President, Major G. P. Bulman, C.B.E., F.R.Ae.S., and Mrs. Bulman, photographed on their arrival at White Waltham by a Westland Sikorsky S.51 helicopter, flown by D. Colvin.

Group Captain R. G. Slade, chief test pilot of the Fairey Aviation Co. Ltd., was in charge of flying, and the Council pay special tribute to him and to Mr. S. M. Moseley and Mr. V. G. Robb for their work in connection with the flying programme, and to Mr. B. J. Hurren, of the Fairey Aviation Co. Ltd., who gave a broadcast description of the events during the afternoon, assisted by Mr. C. S. Watkinson, of the de Havilland Engine Co. Ltd.

The Society is greatly indebted to the many private owners and to the following for making the aircraft available: The Air Historical Branch of the Air Ministry; Auster Aircraft Ltd.; Blackburn and General Aircraft Ltd.; The Bristol Aeroplane Co. Ltd.; The College of Aeronautics; The de Havilland Aircraft Co. Ltd.; Hawker Aircraft Ltd.; F. G. Miles Ltd.; The Rotol Flying Club; The Royal Aero Club; The Science Museum; The Shuttleworth Trust (Warden Aviation Co.); The Surrey Gliding Club; and Westland Aircraft Ltd.



Charles E. Brown

Four of The Cody-type Man-lifting Kites rising in line astern on a common cable at the start of their demonstration. The Kites are approximately 12 ft. wide, 10 ft. long and 5 ft. in height and are similar to those built by S. F. Cody about 1905. With "Squadron Leader Sandbags" they reached a height of several hundred feet at the Garden Party.

The flying programme, which began at 3 p.m., was as follows:—

Aircraft	*Owner*	*Pilot*
Miles Aerovan, G-AKHF	F. G. Miles Ltd.	I. A. Forbes
Youngman (High Lift), G-AMBL		D. C. T. Bennett
Cody Kites, and an ascent by the "R" Type Observation Balloon	The Balloon Unit, R.A.F., Cardington	The Balloon Unit, R.A.F., Cardington
Olympia Mk. II Glider, G-ALJZ—towed by an Auster Autocrat, G-AGVJ, owned by the Redhill Flying Club and piloted by Mrs. Ann Douglas	Surrey Gliding Club	F. G. Irving (Graduate of the Society)
Tipsy B, G-AISC	Fairey Aviation Co. Ltd.	C. G. Alington
Swordfish NF.389	Royal Navy; lent by permission of the C.O., R.N.A.S., Gosport.	L. P. Twiss

Aircraft	*Owner*	*Pilot*
Macchi-Bazzocchi M.B. 308, I-TALY	Aeronautica Macchi	Signora Cassini
Bristol Fighter D.8096	The Shuttleworth Trust	A. J. Pegg
Hawker Cygnet, G-EBMB	Hawker Aircraft Ltd.	F. Murphy
B.A.C. Drone, G-AEKV	J. E. Fricker	J. E. Fricker
Sopwith Pup, G-EBKY	The Shuttleworth Trust	R. F. Martin
Blackburn B.2 Trainer, G-ACLD	Blackburn and General Aircraft Ltd.	B. J. Watson
Hirtenberg H.S.9A, G-AGAK		D. D. Budworth
de Havilland 84 Dragon, G-ACIT	British Overseas Airways	T. E. Scott-Chard
Hawker Tomtit, G-AFTA	Hawker Aircraft Ltd.	Neville Duke
Hawker Hurricane, G-AMAU	Hawker Aircraft Ltd.	F. Bullen
Bristol Helicopter Mk. III, G-ALSX	Bristol Aeroplane Co.	C. T. D. H. Hosegood
Blackburn Monoplane	The Shuttleworth Trust	Gordon Banner
D.H. Chipmunk, G-ALWB	The de Havilland Aircraft Co. Ltd.	P. Fillingham

In addition to the many visiting aircraft the following aircraft were shown:—

Aircraft	*Owner*
Autocrat, G-AJIZ	Auster Aircraft Ltd.
Dart Kitten, G-AEXT	W. G. A. Harrison
D.H. Dove, G-ALVF	The College of Aeronautics
Handley Page Gugnunc, G-AACN	Lent from The Aeronautical Collection of The Science Museum
Magister (Hawk Trainer III), G-AIUA	R. H. Young
Percival Mew Gull, G-AEXF	H. E. Scrope
Praga, G-AEUT	Lt. Cdr. A. Goodhart, R.N.
Sopwith Triplane	Air Historical Branch, Air Ministry
Taylorcraft Model "A," G-AFJO	Rotol Flying Club
Westland-Hill Pterodactyl Mk. I	Lent from the Aeronautical Collection of The Science Museum
Westland Sikorsky S.51, G-ALIK	Westland Aircraft Ltd.
Spherical Balloon	Balloon Unit, R.A.F., Cardington
Frost Ornithopter Engine	The Shuttleworth Trust

The Council wish to thank sincerely all those pilots, private owners, aircraft firms, flying clubs and associations, ground crews and others, who helped so willingly and generously with the display of the aircraft, both in the air and on the ground, and made possible the excellent flying programme and interesting exhibits on the ground and in the hangar.

The Council also wish to thank Dr. A. Buchanan Barbour, F.R.Ae.S., Chief Medical Officer, British European Airways Corporation, who was in attendance as Honorary Medical Officer during the afternoon.

In addition the Society wishes to thank the Berkshire Constabulary, the Royal Automobile Club, and the St. John Ambulance and Nursing Brigade for their services and help.

The Society also wishes to acknowledge the ready co-operation and help of The Pyrene Co. Ltd., in arranging the fire fighting equipment; Tannoy Products (Sound Rentals Ltd.) for providing the sound amplifying equipment; The British Legion Car Attendants Co. Ltd., for the car parking arrangements; and all those who so readily contributed to the success of the 1951 Garden Party.

REVIEWS

STANDARD METHODS OF ANALYSIS OF IRON, STEEL AND FERRO-ALLOYS. The United Steel Companies Ltd. Sheffield. 1951. 169 pp. Illustrated. 17s. 6d. net.

Any manufacturing process which aims at producing a material of uniform quality must depend on the exercise of chemical and/or physical control of the progressive changes from the raw material to the final product. In the metallurgical field, the origins of this idea are deep rooted indeed. The Lydian stone, a streak method of estimating the gold content of an alloy, was probably in use 500 years B.C. Theophrastus, two centuries later, mentions analytical methods which we should now term chemical, while yet a century on, bathing Archimedes evolved a most informative physical technique employed even to this day.

So much for the ancients—the purpose of the present writer is to deal with the moderns or, more accurately with the latest edition of a book mainly on methods of analysis of ferrous materials judged, and no doubt rightly judged, by a team of admitted experts, to be the best available. This work, when first published in 1933, was of high quality. Now in its fourth edition, it has by no means departed from its former standard, while its value has been increased by considerable widening of its scope.

The book provides any one, not necessarily familiar with the fundamental chemistry and physics of the processes described, but given reagents of the appropriate strengths and capable of using instruments and also of carrying out with precision clearly set out instructions, with a means of determining the chemical composition of irons, steels, ferro-alloys and fluorspars.

The techniques, the manipulative stages of which are so lucidly outlined, include purely chemical and some physical-chemical ones. In the latter field, the essentials of colourmetric, absorptiometric and polargraphic methods are well described. Nothing, however, is said of the immense utility of the spectroscope as a means of carrying out certain determinations both of a qualitative and of a quantitative nature —doubtless the authors deem this merits a volume to itself.

This book has many valuable qualities. The methods of analysis are given with the precision of an Instructional Sergeant Major. There is an absence of historical background comparable with that of a railway timetable. Not a single chemical equation throws light on the reactions being employed, while its functional utilitarianism places it in the same class as Mrs. Beaton's cookery book. It is, in fact, a splendid guide for those who require accurate results without wishing to know to whom or to what chemical and/or physical mechanism they are indebted for their achievement. Workers in industrial laboratories will find it of the utmost use. Teachers of analytical chemistry will deplore that it makes unnecessary the learning they are wishing to impart.

DIESEL MODEL ENGINES. Lt.-Col. C. E. Bowden. Percival Marshall & Co. 1951. 216 pp. 127 illustrations. 9s. 6d. net.

A revised edition of this book, first published in 1947, has now appeared. It contains up-to-date details of British and foreign types of model diesel engines and descriptions of various aircraft, boats and cars in which they are installed; the use of radio control for these models is also included.

The six chapters also cover design, installation and working of diesels, fuel and lubrication, starting, problems of operation and trouble finding.

As with the earlier editions, this is a most useful book for the model enthusiast.

CORRESPONDENCE

A NOTE ON THE BUCKLING OF STRUTS

In a paper by Dr. H. Lurie (March 1951 JOURNAL, pp. 181-184) the surprising statement is made that the usual method of computing buckling loads of struts can not always yield all possible modes of buckling. It does not seem superfluous to show the falseness of this statement and I shall use the same example of a column fixed at both ends.

It is clear that in trying to find all possible modes, we may not restrict ourselves to symmetrical or anti-symmetrical boundary conditions and should therefore admit a shear force as well as a bending moment, say Q_1 and M_1, at one of the ends, say $x=l$. Q_1 and M_1 should be treated as independent quantities. The differential equation then is

$$EI\,y'' = Q_1(l-x) + M_1 - Py\,,$$

or

$$y'' + k^2 y = -\frac{Q_1 x}{EI} + \frac{Q_1 l + M_1}{EI}\,, \qquad . \quad . \quad . \quad (1)$$

where dashes denote differentiation and $k^2 = P/EI$. The solution is

$$y = A\sin kx + B\cos kx + Cx + D\,.$$

The boundary conditions $y=0$ and $y'=0$ at $x=0$ yield $B=-D$ and $kA=-C$, so that

$$y = A(\sin kx - kx) + D(1-\cos kx)\,.$$

The boundary conditions at $x=l$ are

$$A(\sin kl - kl) + D(1-\cos kl) = 0\,,$$

$$kA(\cos kl - 1) + kD\sin kl = 0\,.$$

Eliminating D from these equations

$$(\sin kl - kl)\sin kl + (1-\cos kl)^2 = 0\,, \qquad . \quad . \quad . \quad (2)$$

which is identical to Lurie's stability criterion (10) and yields *both* the symmetrical and the anti-symmetrical modes of buckling.

If the usual method of determining the particular solution $Cx+D$ is followed, only two boundary conditions can be used to determine A and B, *e.g.* $y=y'=0$ at $x=0$. Then

$$y = \frac{Q_1}{kP}(\sin kx - kx) + \frac{Q_1 l + M_1}{P}(1-\cos kx)\,. \qquad . \quad . \quad (3)$$

The stability criterion can now be determined by noting that $EI\,y''=M_1$ and $EI\,y'''=-Q_1$ at $x=l$. From these two equalities the *complete* stability criterion (2) is again found. This method is more involved than the first and in order to avoid its complications it is fairly obvious to differentiate equation (1) twice, thus obtaining

$$y'''' + k^2 y'' = 0 \qquad . \quad . \quad . \quad (4)$$

which is Lurie's equation (5), and so on.

Still another method is to write equation (4) in the form

$$M''+k^2M=0 \quad . \quad . \quad . \quad (5)$$

and solve this second order differential equation. Now

$$M=A\sin kx+B\cos kx,$$

$$x=0:\ M=B=M_1+Q_1 l,$$

$$M'=kA=-Q_1,$$

$$x=l:\ M_1=B+kA\,l=A\sin kl+B\cos kl,$$

$$-Q_1=kA=kA\cos kl-kB\sin kl.$$

From the latter two equations the complete stability criterion is again found. The conclusion therefore may be that the use of equations (1), (4) or (5) is purely a matter of convenience, not of principle.

F. J. Plantema, *Amsterdam*

Dr. Lurie implies that a second order differential equation cannot give a general solution to the strut problem considered. This is not so, for, if the general case is taken as that of a strut having an axial load P, a fixing moment M_0, and a transverse shear R at one end where $x=0$, then the conventional second order differential equation of equilibrium for small displacements is

$$\frac{d^2y}{dx^2}=a+bx-k^2y,$$

where

$$a=\frac{-M_0}{EI},\quad b=\frac{R}{EI},\quad k^2=\frac{P}{EI}.$$

The general solution of this equation is

$$y=A\cos kx+B\sin kx+(a+bx)/k^2.$$

For a fixed ended strut, this equation and the boundary conditions

$$(y)_{x=0}=(y)_{x=l}=0;\left(\frac{dy}{dx}\right)_{x=0}=\left(\frac{dy}{dx}\right)_{x=l}=0$$

lead to the equations

$$a(1-\cos kl)=-bl+(b/k)\sin kl$$

$$a(1-\cos kl)=bl\cos kl-(b/k)\sin kl.$$

A solution $(1-\cos kl)=0$ is obtained if $b=0$, corresponding to the classical solution $kl=2\pi n$, and end conditions $M_0=M_l$, $R=0$.

If $b\neq 0$ then

$$-l+\frac{k}{\sin kl}=l\cos kl-\frac{\kappa}{\sin kl}$$

giving

$$\tan\frac{kl}{2}=\frac{kl}{2},$$

the "additional" solution to which Dr. Lurie draws attention.

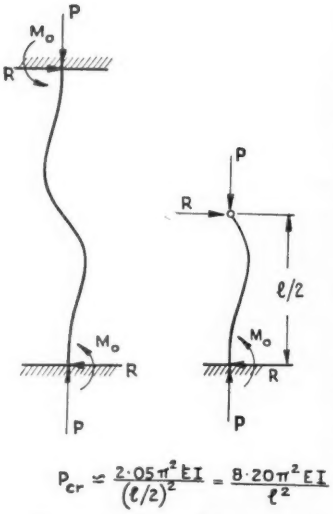
In this case $b=-2a/l$, and the end conditions are $M_0=-M_l$, and $R=2M_0/l$.

H. Waters, M.Eng., A.M.I.C.E.,
Civil Engineering Dept., University of Liverpool.

Dr. Lurie's plea in favour of the fourth order differential equation for the buckling of struts unfortunately discredits unjustly the derivation by means of the second order bending moment equation. Both procedures are fully equivalent, when applied correctly, because the second order equation contains in the general case two independent unknown constants, namely the bending moment and the shear reaction at one end of the strut. These constants and the additional two constants of integration are determined by the four boundary conditions. For the beam with both ends clamped both the symmetrical and the anti-symmetrical buckling modes with the sequences of critical loads (11) and (12) are then obtained correctly.

However, if the end reactions for a strut with both ends clamped are assumed either symmetrical or anti-symmetrical – Fig. 4(*a*) or Fig. 4(*b*) of Dr. Lurie's note— the second order equation contains only one independent constant and only the symmetrical or the anti-symmetrical buckling mode is obtained with the corresponding sequence of critical loads. Dr. Lurie's criticism of the classical approach should therefore not be directed at the second order equation itself but at the initial assumption regarding the distribution of end reactions.

W. T. Koiter, *Associate Fellow*,
Professor of Applied Mechanics, Laboratorium Toegepaste Mechanica, Delft.



$$P_{cr} \simeq \frac{2{\cdot}05\pi^2 EI}{(\ell/2)^2} = \frac{8{\cdot}20\pi^2 EI}{\ell^2}$$

A few words in the defence of the "classical solution" may not be out of place. Clearly, the apparent fallacy of the method is due to misapplication, and the solution derived by the author is that for a strut fixed at the centre, both in position and direction.

Admittedly the approach usually adopted in engineering text books does appear unattractive when compared with the author's vigorous model analysis. However it is the fundamental mode that is of practical importance, and it has been always accepted, if tacitly.

Had the author persisted in vigour, defined the restraint imposed, and solved the mathematically and physically obvious case of the fixed-pin strut as shown, no confusion would arise.

In a similar way, the correct solution may be found for any well-defined set of restraints.

J. M. Tusiewicz

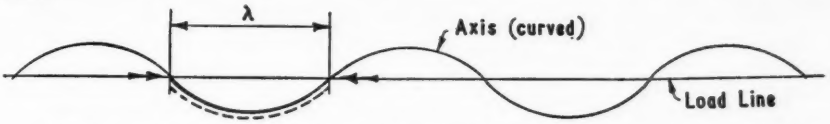
For some years I have approached most strut buckling problems by means of the equation

$$y = A \sin \frac{\pi x}{\lambda} + B \cos \frac{\pi x}{\lambda} + Cx + D,$$

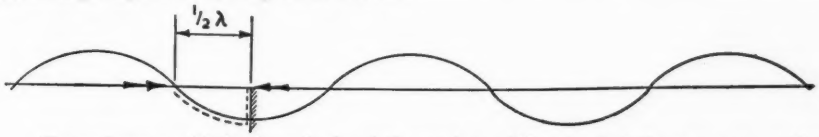
which is similar to the equation midway between equations (6) and (7) in Dr. Lurie's paper. This equation has a physical significance which assists in its interpretation. The first two terms on the right side define an equilibrium configuration of a compressed strut, referred to the line of action of the load. (Note that the inflection points lie along this line.) The two remaining terms serve simply to refer the curve to any other reference axis. The parameter λ is one half wave length of the curve. It can be given in terms of end load and section properties, but is most useful for comparing directly different end conditions.

With this background the solution of buckling problems becomes one of fitting the end conditions to this curve. For the basic "Euler" column, the condition

that the load pass through the ends of the strut gives a simple half wave length curve.

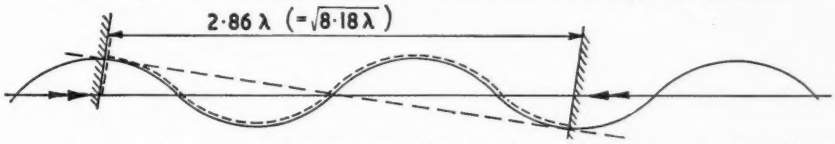


For a vertical column with a vertical load applied at the top, the load line passes through the axis at the top, and parallel to a tangent to the axis at the bottom, giving the following construction:



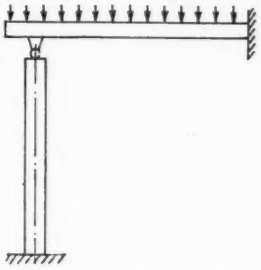
For columns with both ends fixed the end condition is that the tangents at the two ends must coincide. This leads to the series shown in Dr. Lurie's Fig. 2 when both tangents are on the same side of the load line.

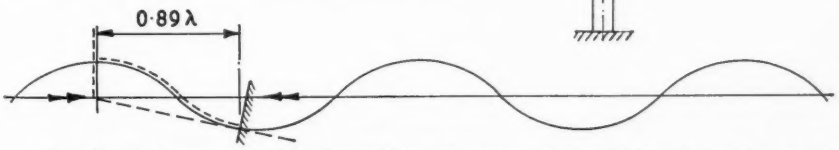
(Note that the load does not pass through the ends as in Dr. Lurie's sketch.) When the tangents are on opposite sides the series shown in Fig. 3 is obtained.



(Note in this case that the load is inclined to the original column axis.) (Also note that this is twice the length of a column fixed at one end and hinged at the other.)

An interesting example that I encountered a few years ago was that of a cantilever with a flat bearing plate at the top and the load applied at a point fixed laterally, through a roller. The condition that the load should be parallel to the axis at the top (*i.e.* normal to the bearing plate) and that its point of application should lie on an extension of the tangent to the axis at the bottom, led to the following construction.





In all of these examples the relation between λ and the column length is readily derived from the geometry of the figures. I must admit that in spite of the simplicity of this approach, the configurations shown in Fig. 3 had not previously occurred to me.

David B. Hall,
Structures Designer,
The Glenn L. Martin Company, Baltimore.

DR. LURIE'S REPLIES

Both Messrs. **Plantema** and **Waters** have had to use four boundary conditions, and mathematically this requires the use of the fourth order homogeneous differential equation in order to obtain a complete solution. They have approached the problem by including two terms in their second order equation which anticipate compatability with two of the four boundary conditions. This is equivalent to partially solving the basic fourth order equation and reducing it to a second order non-homogeneous equation, thereby making their solution equivalent to mine. Provided the general equation for the column deflection is determined as

$$y = A \sin kx + B \cos kx + Cx + D$$

in every case, all buckling modes will be obtained. The usual method introduced to students first considers a pin-ended strut, and then extends the procedure to fixed ends by adding one more moment term to the second order differential equation. Hence the general equation for the column deflection is not obtained. The four constants in the above general equation indicate that it is a solution of a fourth order differential equation.

The comments of Messrs. Plantema and Waters are appreciated in presenting an alternative procedure which helps to emphasise the fundamental application of the buckling equation.

Professor Koiter's comments on the equivalence of the two methods are entirely correct. However, the object of my paper was to indicate the lack of generality in using the second order equation as presented in engineering text-books. If one inserts the correct end reactions for a *particular* mode of buckling, naturally the corresponding critical load is obtained. But the use of the fourth order equation obviates the necessity of knowing in advance the mode of buckling. It is this knowledge which is a pre-requisite to a correct interpretation of the second order equation.

The above remarks also apply to the comments of **Mr. Tusiewicz**, who, however, erroneously stated that my solution was that for a strut fixed at the centre, both in position and direction. Figure 2(c) clearly indicates that this is not the case. The example worked out in the paper gives *all possible modes* for a strut clamped at both ends.

Mr. Hall has produced a very interesting physical interpretation of the general solution to the buckling problem. His resulting geometrical approach is useful not only as a tool, but also as a means of gaining a basic understanding of the problem. In his examples with both ends fixed, the load does not pass through the ends because a moment is produced. In both of his sketches illustrating this, the moments produced at the ends are in the correct directions and correspond to those shown in Fig. 4 of the paper. In his unusual final example, the mathematical boundary conditions are:

$$\text{At } x=0,\ y=0 \text{ and } dy/dx=0$$

$$\text{At } x=l,\ d^3y/dx^3=0 \text{ and } EI\frac{d^2y}{dx^2} = -Py.$$

Substituting these into the general solution yields the transcendental equation

$$kl \tan kl = -1.$$

Therefore $kl = 2.798$

and $$P_{cr} = \frac{0.793\,\pi^2 EI}{l^2}.$$

Hence $l = \sqrt{0.793}\,\lambda = 0.89\,\lambda$, agreeing with Mr. Hall's geometrical solution.

Harold Lurie, Ph.D., *Associate Fellow*

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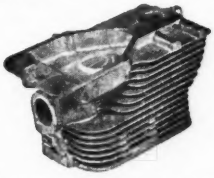

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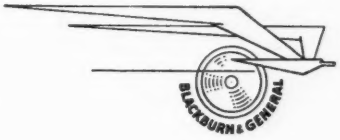

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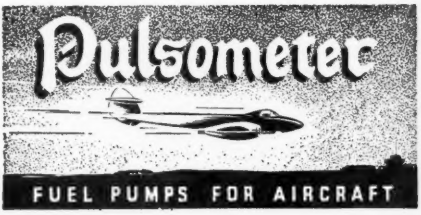

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